Economic Analyses of Microalgae Biofuels and Policy Implications in Australia

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Statement of original authorship

The work contained in this thesis has not been previously submitted for a degree or diplomas at this or any other higher education institution. To the best of my knowledge and belief, this thesis contains no material previously published or written by another person except where due reference is made.

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Abstract

Biofuels represent a key substitute in the transport fuel market. However, the literature has identified significant economic costs associated with conventional biofuel feedstocks, particularly opportunity costs with crop and agricultural resource allocation. This suggests the potential for a new biofuel feedstock, microalgae. Unlike conventional feedstocks, microalgae biofuels can reduce pressure on resource allocation and can bio-fixate waste streams from other industries. However, with the literature of this infant technology not addressing key economic aspects, essential policy support has been scarce.

The research undertaken in this thesis aimed at addressing broader economic benefits and costs, determining the efficiency of policy support for microalgae biofuels. Firstly, a comprehensive review outlined the issues with conventional biofuels and suggested the economic prospects of microalgae biofuels and informed the design of the rest of the studies in this thesis. Then, a techno-economic analysis, used commonly in process engineering, was conducted for hypothetical microalgae biodiesel production. Unlike much of the literature that has used this method, this analysis incorporated elements of multiple outputs and integration with complementary industries. The results suggested the potential to achieve financial feasibility through these two aspects. The subsequent study covered an extension to the techno-economic analysis: the derivation of a multi-output profit function. This was accomplished by modeling production scenarios simulated in the previous techno-economic model. The findings illustrated the relationship between price, output mix, and profitability, which can inform decision-making for a producer. Following this, an analysis of the non-market value for biofuels was undertaken using discrete choice experiments. This revealed how consumers exhibited a substantial willingness to pay for the externalities associated with alternative biofuels, like those from microalgae.

Given that policy has been a key determinant of biofuel industry development, the findings from these economic studies were then incorporated in a discussion on existing policy support for biofuels in Australia and how microalgae biofuels could form a greater part of the policy framework.

Keywords: biofuels, discrete choice experiments, externalities, microalgae, multi-output, non-market value, policy, profit function, techno-economic analysis

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Abbreviations

ACT	Australian Capital Territory
AIC	Akaike's Information Criterion
ANA	Attribute Non-Attendance
AUD$	Australian Dollar
B5	Biodiesel-diesel blend (5%)
CA	Conjoint Analysis
CEPCI	Chemical Engineering Plant Cost Index
CO_2	Carbon Dioxide
CVM	Contingent Valuation Method
DAP	Diammonium Phosphate
DCE	Discrete Choice Experiment
E10	Ethanol-petrol blend (10%)
EPG	Ethanol Production Grant
EROI	Energy Return on Investment
EU	European Union
FAME	Fatty Acid Methyl Ester
FCI	Fixed Capital Investment
GHG	Greenhouse Gases
HTL	Hydrothermal Liquefaction
IIA	Independence of Irrelevant Alternatives
IID	Independently and Identically Distributed
INA	Inferred Non-Attendance
LCM	Latent Class Model
LPG/CNG	Liquefied Petroleum Gas/Compressed Natural Gas

LRP	Lead-Replacement Petrol
MEA	Monoethanolamine
MNL	Multinomial-Logit
NPV	Net Present Value
NSW	New South Wales
NT	Northern Territory
PBR	Photo-Bioreactor
PULP	Premium Unleaded Petrol
QLD	Queensland
RP	Revealed Preference
RPL	Random Parameters Logit
RULP	Regular Unleaded Petrol
SA	South Australia
SNA	Stated Non-Attendance
SP	Stated Preference
SV	Switch Value
TAG	Triacylglyceride
TAS	Tasmania
TEA	Techno-Economic Analysis
US$	United States Dollar
USA	United States of America
VIC	Victoria
WA	Western Australia
WTP/WTA	Willingness to Pay/Willingness to Accept

Chapter 1. Introduction

1.1. Overview

The security of supply of fossil fuels is jeopardised by increasing demands through population growth and instability in fossil fuel producing regions (Gavrilescu & Chisti, 2005). Electric and gaseous-powered (e.g. natural gas and liquefied petroleum gas, LPG) alternatives require costly investments from consumers in the form of new vehicles or modifications to existing vehicles (Karatzos, McMillan, & Saddler, 2014). As a result, the development of biofuels that can be readily substituted into existing vehicles (Agarwal, 2007; Çelikten, Koca, & Arslan, 2010) represents a key element in the global transport fuel market.

Although biofuels are currently only a small proportion of global transport fuel consumption at 1.9%, trends have suggested a threefold increase in the next 20 years (L. Carson, 2014). The main driver of this growth is expected to come from increasing policy support. This is based on proactive government intervention having supported the growth of biofuel industries in Brazil and the United States of America (USA) (Goldemberg & Guardabassi, 2009). From a neoclassical economics perspective, this support of production will likely result in an increase in supply of biofuels, lowering prices for consumers, *ceteris paribus*. However, much of the current conventional feedstocks are based in terrestrial agriculture, which raises opportunity costs with food-crop and resource allocation. The external costs associated with these biofuel feedstocks may counteract the benefits of the market transition, leading to a less socially optimal outcome.

An increasing body of literature has suggested that a new biofuel feedstock, microalgae, can alleviate issues that have plagued its biofuel predecessors, particularly in impacts to food-crop and resource allocation (Chisti, 2008). The science and engineering disciplines have heavily dominated the discussion on microalgae biofuels. Whilst these help to investigate the developments of the production technologies, broader economic analysis is required to ascertain the need for policy intervention and the resulting impacts, particularly in the presence of externalities.

This thesis aims to address this gap by undertaking an economic analysis of microalgae biofuel production and consumption. The results of this analysis are used to inform how policy in Australia can be reframed for this new transport fuel technology.

1.2. Brief introduction to biofuels

There are generally two types of biofuels: ethanol (or biopetrol) made from carbohydrates (sugars) and biodiesel made from lipids (fats). Biofuels can be derived from biological material like plants, animal fats, and other sources. However, plant-based feedstock has attracted significant interest to sustainably meet current and future fuel demands (Singhania, Parameswaran, & Pandey, 2008). As such, this thesis will focus on plant-based biofuels rather than from animal and other sources.

The classification of biofuels varies across disciplines according to details on feedstock type and conversion technology. In order to avoid confusion, the classification of biofuels that will be referenced in this thesis is based on the feedstock type as outlined in Table 1.1.

Table 1.1: Classification of biofuels

Biofuel class	Feedstock characteristics	Examples of biomass (biofuel)
Conventional biofuels		
First-generation	Food-based crops	Corn, sugarcane molasses (ethanol) Soybean, rapeseed (biodiesel)
Second-generation	Non-food crops	Forest residues, sugarcane bagasse (ethanol) Jatropha (biodiesel)
Alternative biofuels		
Third-generation	Microscopic biomass	Microalgae (ethanol, biodiesel)

Conventional biofuels are subdivided into first and second-generation biofuels[1]. First-generation biofuels have proliferated in certain fuel markets (L. Carson, 2014), especially ethanol in the USA (made from corn) and Brazil (made from sugarcane) and various oil-based crops for biodiesel in Europe (Gasparatos, Stromberg, & Takeuchi, 2013). However, a key concern with regards to first-generation biofuels is the trade-offs of 'food versus fuel'. This occurs because both food and first-generation biofuel production utilise the same crops and/or agricultural resources (namely arable land and water), creating opportunity costs in resource allocation decisions.

Second-generation feedstocks that can produce similar liquid biofuels from non-food crops were developed as a response to this concern, as it could reduce the competition for food-crops. However, the issue of resource allocation was not completely avoided with second-generation biofuels. The opportunity costs from the reallocation of arable land and water still exists with these biofuels. These costs can be particularly detrimental to agricultural-based communities in poorer regions (Clancy, 2008; Rajagopal, 2008). Policy support for fuel security through first and second-generation biofuels will likely exacerbate the opportunity costs of agricultural resource allocation, as it directly competes with objectives of food production policies.

[1] For a comprehensive list of first and second-generation biofuel feedstocks, see paper by Azad, Rasul, Khan, Sharma, and Hazrat (2015).

Third–generation feedstocks for biofuels are generally microscopic biomasses that can be cultivated in controlled, artificial environments and are less reliant on scarce resources such as food-crops, arable land, and water (Dragone, Fernandes, Vicente, & Teixeira, 2010; Singh, Nigam, & Murphy, 2011a; Singh, Olsen, & Nigam, 2011b). Additionally, the cultivation of microalgae can utilise nutrients from waste streams like municipal wastewater and carbon emissions from power plants. Microalgae can be processed to produce both biodiesel and ethanol. There are an increasing number of studies investigating the developments of microalgae biofuels given the fuel production efficiency of the technologies (Azad et al., 2015) that suggests the ability to meet current and future fuel demands (Chisti, 2007), whilst avoiding economic issues plaguing conventional biofuels. While financial (e.g. Davis, Aden, & Pienkos, 2011; Pokoo-Aikins, Nadim, El-Halwagi, & Mahalec, 2010), energy (e.g. Lardon, Hélias, Sialve, Steyer, & Bernard, 2009; Sander & Murthy, 2010), and carbon costs (e.g. Clarens, Resurreccion, White, & Colosi, 2010; Ono & Cuello, 2003) of microalgae biofuels have been well documented in the literature, the economic benefits described above have not been explicitly analysed, particularly from a broader economic perspective.

1.3. Existing literature and gaps in microalgae biofuel research

The current body of research on microalgae biofuels has been focused in the science and engineering disciplines. These studies assess and develop the technical and financial feasibilities in cultivation, harvesting and dewatering, and conversion to relevant output products, through experimental set-ups (Briassoulis et al., 2010; Huntley & Redalje, 2007; Odlare et al., 2011). Some studies have also presented hypothetical scaling-up of production facilities to suggest technical and financial viability in larger production scales through different inputs and process pathways. These include assessments on the net energy return

(Brennan & Owende, 2010; Brentner, Eckelman, & Zimmerman, 2011), and net carbon emissions (P. K. Campbell, Beer, & Batten, 2011) and nitrogen (Batten et al., 2013; Christenson & Sims, 2011; Hoffmann, 1998).

The extent of 'economic' analyses into microalgae biofuels has been limited to financial valuation in these hypothetical production studies, primarily of biodiesel[2] production. These include assessing the financial feasibility of current production technologies (Alabi, Tampier, & Bibeau, 2009; Lundquist, Woertz, Quinn, & Benemann, 2010; Taylor et al., 2013), sensitivities of estimates to changes in input variables (Davis et al., 2011), and the effects of risk in the production expenditure (Richardson, Johnson, & Outlaw, 2012). The financial estimates have suggested that the potential for microalgae biofuel production is hindered by the larger production costs and uncompetitive unit prices relative to petrol and diesel derived from crude oil (Alabi et al., 2009; P. K. Campbell, Beer, & Batten, 2009; Richardson et al., 2012). Some studies (Alam et al., 2012; Slade & Bauen, 2013) have indicated the potential of multiple/alternative output allocations from the resulting biomass to improve financial feasibility, but there has been no attempt to model this.

In addition, with the lack of commercial production, there is limited study into the impacts of price fluctuation on the feasibility of production. Currently, the incorporation of price fluctuations has been limited to sensitivity analyses (Davis et al., 2011; Norsker, Barbosa, Vermuë, & Wijffels, 2011; Stephens et al., 2010). Borowitzka (2013) suggests that a weakness in such studies is that they are limited to single parameters rather than simultaneous fluctuations across all prices. The alternative would be utilizing stochastic production simulations but these have focused more on alternative production parameters (Delrue et al.,

[2] It will be detailed later in this thesis that biodiesel production is often the focus of microalgae biofuel research due to the efficiency of lipid/fat accumulation in the biomass that is converted into biodiesel.

2012; Fortier, Roberts, Stagg-Williams, & Sturm, 2014; Richardson, Johnson, Lacey, Oyler, & Capareda, 2014) or investment risk analysis (Richardson et al., 2012). There is a gap in the understanding of how price fluctuations might affect a potential investor or producer given current or projected technologies. Also, with the potential of a multi-output system, the impacts of price fluctuations on the output mix would provide key information to these potential stakeholders. This information could prove crucial for private and public investment in this technology.

Furthermore, there is a lack of economic analyses of microalgae biofuels outside of the production and financial valuation studies. While the latter are pertinent given the infancy of the microalgae biofuel technologies, understanding the economic aspects is key to identifying the need for policy intervention. Such economic analyses illustrate the costs and benefits in a broader context, involving consumers/society and providing information to assist policymakers. In particular, understanding and quantifying the relative benefits of alternative biofuels over their conventional counterparts could help inform the relevance of proactive government support for alternative feedstocks like microalgae. While this has been attempted to some extent for conventional biofuels (Jeanty & Hitzhusen, 2007; Petrolia, Bhattacharjee, Hudson, & Herndon, 2010), the hypothetical nature of alternative biofuels has left a gap in this aspect of the literature.

Consequently, the lack of economic analysis of microalgae biofuels has hindered discussion on the influence of policy support on the potential uptake of microalgae biofuels in Australia. The importance of policies dedicated to biofuel development and consumption has been evident in countries like USA and Brazil (Fulton, Howes, & Hardy, 2004; Goldemberg & Guardabassi, 2009), and parts of Europe (Gasparatos et al., 2013). The literature has highlighted the potential for microalgae biofuels as a significant biofuel alternative in Australia. This is due to the availability of land, ideal climate conditions, and potential for complementary production and utilising by-products/waste from existing industries (Kosinkova et al., 2015a). However, policy support for developing a larger biofuel industry and market has been limited in Australia beyond an underachieving mandate in New South Wales (NSW) and a recent mandate in Queensland (QLD). As such, designing an efficient policy framework for Australia will be dependent on understanding the benefits and costs of microalgae alternatives, and the most efficient allocation of resources for supporting its development.

1.4. Research hypothesis

The qualitative literature in the science and engineering discipline has consistently highlighted the opportunities for microalgae biofuels as a long-term alternative to fossil fuels. Despite this, there is lack of policy recognition and support of these technologies. At first glance, this could be attributed to the infant nature and associated uncertainty of this technology. However, there may be an economic rationale that could substantiate public investment in the development of microalgae biofuels, particularly through positive externalities. Hence the research undertaken in this thesis is based on the hypothesis that there may be economic value from the production and consumption of microalgae biofuels, currently unassessed in the literature, that could justify or negate the need for policy intervention.

1.5. Research objective and aims

The main objective of the research outlined in this dissertation is to investigate the economic benefits and costs of microalgae biofuels, and suggest related policy recommendations in

Australia. This objective is addressed by focusing on three areas: production, consumption, and policy. This is achieved by responding to the following research questions:

1. Based on the current knowledge of biofuels, what are the economic benefits of microalgae biofuels to warrant their consideration as a long-term transport fuel alternative?
2. How can the financial feasibility of microalgae biodiesel production be improved through an integrated system with multiple outputs?
3. How sensitive are the financial parameters of microalgae biodiesel production to fluctuation in input and output prices?
4. What are the non-market values of the externalities from biofuel consumption?
5. Given the findings from the previous studies, what are the key areas that policy should address in supporting development of microalgae biofuels?

These research questions were addressed systematically in the following research aims, as summarized in Table 1.2.

Aim 1: Review the current state of biofuels globally and compare economic benefits that microalgae biofuels can potentially provide relative to conventional biofuels.

The literature investigating various aspects of conventional biofuels is relatively well established. In particular, the proliferation of first-generation biofuels has allowed for more policy-related study into the impact of biofuels on consumer markets (Fulton et al., 2004; Gasparatos et al., 2013; Hill, Nelson, Tilman, Polasky, & Tiffany, 2006; Martinot, 2005), non-market benefits (Ahn, Jeong, & Kim, 2008; Bunch, Bradley, Golob, Kitamura, & Occhiuzzo, 1993), and opportunity costs in relation to food and resource security (Bastianin, Galeotti, & Manera, 2013; Msangi, Sulser, Rosegrant, & Valmonte-Santos, 2007; Prabhakar

& Elder, 2009; Timilsina, Mevel, & Shrestha, 2011). There has also been some theoretical study into the impact of mandated biofuel policy on the resulting fossil fuel consumption (de Gorter & Just, 2007, 2008, 2009; Drabik, 2011) and the counter-productive effect on biofuel-fossil fuel blends (Grafton, Kompas, & Long, 2010; Kalkuhl, Edenhofer, & Lessmann, 2013). In contrast, research on microalgae biofuels outside of production analyses has been limited. This is in spite of the fact that microalgae biofuels avoid the key limitations that have remained present with their predecessors, particularly with food-crop and resource allocation.

The review of the available literature for both conventional and third-generation biofuels illustrated the current state of research in biofuels. The findings from this review set the context for the subsequent quantitative studies that addressed the main objective in this thesis.

Aim 2: Estimate the financial feasibility of microalgae biofuel production through techno-economic analysis in a multi-output system integrated with complementary industries.

This represents the production-based study of this dissertation. The review of the literature suggests a gap in the technical and financial analysis of microalgae production. Microalgae biofuels are not financially feasible due to uncompetitive price estimates (Davis et al., 2011; Davis et al., 2014). However, less quantitative literature (Borowitzka, 2013) has suggested feasibility through production of multiple outputs. This study models multiple alternative/co-product allocations for the microalgae biomass through a sensitivity analysis to ascertain if such systems can improve the financial feasibility of microalgae biofuels.

The techno-economic model (a production-based financial valuation tool used in the process engineering discipline) employed for this analysis was based on those used in the process engineering discipline, in particular, Darzins, Pienkos, and Edye (2010). This study models the production of biodiesel specifically (rather than ethanol), due to the efficiency of lipid/fat accumulation in microalgae biomass that can be converted to biodiesel (S. A. Scott et al., 2010), which has driven much of the current research interest. The use of engineering models in this study (which will be detailed later in this document) allowed for a more detailed analysis of the production process and improved the accuracy of the hypothetical production model to estimate the financial feasibility. The model was then used to determine the areas of the production system where technical improvements (and cost reductions) can be made to improve the financial feasibility of producing the biodiesel. Although there were a number of such studies in the literature pertaining to larger-scale intensive microalgae production and sensitivities to various input variables (Davis et al., 2011; Pokoo-Aikins et al., 2010), the production model in this study incorporated detailed analysis of multiple outputs and examined the trade-offs of input variation with the most viable output allocation. Additionally, the use of waste effluents from other industries was factored into the analysis, which illustrated the potential for integrated production systems for microalgae biodiesel.

The existing techno-economic models have been focused on the technological aspects of production. This study extended this methodology by including a multi-output system, integrated with complementary industries to yield greater financial and economic benefits. The model designed in this study also formed the basis for the study of Aim 3.

Aim 3: Illustrate the impact of price fluctuations on the potential profit of a microalgae producer.

The current production literature for microalgae biofuels attempts to account for variability and fluctuations through sensitivity analyses (Davis et al., 2011; Norsker et al., 2011; Stephens et al., 2010). These analyse individual parameters in isolation to illustrate the impact of such fluctuations on the final metric of interest. While useful in determining the direction of research and development from a technological development aspect (Borowitzka, 2013), this approach does not adequately identify the relationship between prices and profits. This is particularly evident when considering the output mix for a multi-output production system. Such analysis would often require econometric analysis of production and market data; but with large-scale production being limited to hypothetical studies; such analysis has not yet been attempted.

The parameters from the production-based analysis from Aim 2 was extended in this study through the use of simulated production scenarios to derive a restricted profit function econometrically. The use of simulations in techno-economic analysis was not necessarily novel, particularly with its use in risk analysis (Richardson, 2010; Richardson et al., 2014; Richardson et al., 2012). However, this study represented a new use of techno-economic simulations by deriving a profit function of multi-product firm (Squires, 1987), similar to its use in aquaculture (Pascoe, Vieira, Dichmont, & Punt, 2011). This study informed the relationship between endogenously fluctuating prices and the profit maximization of a multi-output production system for microalgae.

Aim 4: Derive the consumer preferences for biofuels and the non-market value of the external benefits of different feedstocks.

While the production-based studies address key aspects in the financial analysis of microalgae biofuel production, this fourth aim addresses the non-market value of biofuels through a study of consumer preferences. This study focused on if and how much consumers would be willing to pay for alternative biofuels with their associated benefits (which will also be outlined further in this document). These external benefits are often not explicitly valued in the price of fuels but may potentially have implicit value for consumers. The non-market valuation techniques can derive a monetary value based on what consumers would hypothetically pay (also known as their willingness to pay (WTP) in economic literature) for a biofuel and its related attributes. This would allow for the derivation of values for positive externalities.

Currently, there is no commercial production and consumption of third-generation biofuels (Olivieri, Marzocchella, Andreozzi, Pinto, & Pollio, 2011). While there was the potential to investigate consumer demand for conventional biofuels based on revealed preferences, deriving the demand specifically for alternative biofuels (e.g. third-generation) would not be possible with such techniques. Hence, preferences would need to be established based on hypothetical scenarios, also known as stated preference techniques. These are established techniques and have been employed to estimate consumer preferences for alternative energy in transport (Jeanty & Hitzhusen, 2007; Solomon & Johnson, 2009), electricity (Nomura & Akai, 2004; Roe, Teisl, Levy, & Russell, 2001), and energy in general (Scarpa & Willis, 2010; Zografakis et al., 2010). This study focused specifically on biofuels in transportation. The design of attributes and related prices in this study drew upon findings from the review chapter, and values the external benefits from the production and use of microalgae biofuels.

Aim 5: Identify how current policies in Australia could be re-framed to incorporate the economic benefits of conventional and alternative biofuels.

The final aim for this thesis was to address the policy aspects of biofuel production and consumption, particularly in a market transition away from fossil fuels. This involved outlining the current biofuel policies in Australia and suggesting efficient alternative policies for transitioning the current transport fuel market to biofuels. As previously established, the key benefit of biofuels is that they are closer substitutes for fossil fuels. There is currently limited use of biofuels in Australia despite the suggested potential capacity for increased production (Kosinkova et al., 2015a). Given evidence of policy influence over a market transitioning to biofuels (e.g. Brazil), this chapter presented a review of current biofuel policies in Australia. Also, more importantly, this study suggested policy recommendations to include alternative biofuels based on the quantitative findings from the previous studies on the economic benefits of microalgae biofuels.

1.6. Thesis layout

The rest of this thesis will be outlined as follows. Chapter 2 covers an in-depth literature review addressing conventional and alternative biofuels, with focus given to the environmental and socio-economic issues and the potential of microalgae as a biofuel feedstock (Aim 1). Chapter 3 will present the analysis of microalgae for biodiesel production with complementary by-products using the techno-economic analysis approach (Aim 2). Chapter 4 will detail the extension of the techno-economic analysis through the derivation of a multi-output profit function (Aim 3). Chapter 5 will cover the consumer preference analysis of fuel consumers in Australia using the discrete choice experiments (Aim 4). Chapter 6 will describe the current policies surrounding biofuels in Australia and suggest policy recommendations to include alternative biofuels (Aim 5). Lastly, Chapter 7 will outline an overall discussion of the findings from the economic analyses undertaken in this project, based on the intended research aims.

Table 1.2: Summary of research aims and description of individual studies.

Aim	Aim 1	Aim 2	Aim 3	Aim 4	Aim 5
Description	Review the current state of biofuels globally and compare economic benefits that microalgae biofuels can potentially provide relative to conventional biofuels.	Analyze the net financial value of microalgae biofuel production in a multi-output system integrated with complementary industries.	Determine the relationship between input and output prices, and profit maximization in a multi-output production system.	Derive the consumer preferences for biofuels and willingness to pay for external benefits associated with different feedstocks.	Identify current biofuel policies and suggest recommendations to develop biofuel industries in Australia.
Importance	Establish the importance of contributing additional economic analyses to the available literature microalgae biofuels.	Determine the sensitivity of production and how integrated, multi-output systems and technological developments can improve financial feasibility.	Derive the profit function of a multi-output production system and the impacts of endogenous price fluctuations on profit.	Estimate the non-market value of external benefits associated with biofuels.	Illustrate how policy can be used to develop the biofuel industry and transition the market to microalgae biofuels.
Methodology	Literature review of conventional and microalgae biofuels.	Techno-economic analysis.	Deriving the restricted multi-output profit function.	Discrete choice experiment.	Review of existing policies and identifying efficient alternative policies.
Data		Updated production parameters from existing literature and price inputs from secondary sources.	Simulations of production scenarios from techno-economic analysis.	Cross-sectional data from discrete choice experiment survey.	National and state-based statistics for energy consumption and transport fuel use.
Research integration	The economic analysis in this thesis aims to identify (Aim 1) and evaluate the potential economic benefits and costs of microalgae biofuel production (Aims 2 and 3) and consumption (Aim 4), and the resulting direction of policy (Aim 5) involvement in the potential development of a new industry and fuel alternative in Australia.				

Chapter 2. Review of the potential of microalgae biofuels over conventional biofuels

2.1. Introduction

This chapter will outline a review of the literature addressing plant-based biofuel production, use, and related external benefits[3]. This review identified the current state of biofuels globally, and emphasized the contradictions and shortcomings of conventional biofuels as stated in the literature. Although the literature addressed in this review encompassed findings from disciplines outside of economics, effort was made to focus on economic issues, especially those pertaining to externalities associated with production and consumption.

The first section of this chapter will cover an overview of conventional biofuels and highlight the economic issues surrounding energy, carbon benefit, food security, and resource demand. Subsequently, a review of microalgae biofuels will be presented addressing similar topics of energy, carbon benefit, and food and resource demand; but also putting forth benefits in carbon and nitrogen remediation. Finally, a discussion will conclude this chapter, highlighting the opportunities for microalgae as a feedstock for biofuel in the longer term. The findings from this review will help to inform the objectives and direct subsequent analyses undertaken in this thesis.

2.2. Conventional biofuels: an overview

2.2.1. Classification of conventional biofuels

Generally, biofuels are either biopetrol or biodiesel, each being the output of processing carbohydrate and lipid-based feedstock respectively. By convention, biofuels are classified

[3] A version of this review was published in the following article: Doshi, Pascoe, Coglan, and Rainey (2016). Economic and policy issues in the production of algae-based biofuels: A review. *Renewable and Sustainable Energy Reviews, 64*, 329-337. doi:10.1016/j.rser.2016.06.027

based on the type of feedstock (Larson, 2008). Conventional biofuels refer to those that are derived from terrestrial-based feedstock. They are further subdivided into first and second-generation biofuels (Table 1.1). First-generation biofuels employ food-based feedstock, with the most common being ethanol from corn or sugarcane molasses and wheat starch (Puri, Abraham, & Barrow, 2012), and biodiesel from soybean, rapeseed/canola oil, and palm oil (O'Connell et al., 2007), the latter becoming increasingly employed in India, China, and Southeast Asia (Gasparatos et al., 2012; Koh & Wilcove, 2008) as well as current high utilisation in Europe (Escobar et al., 2009; Gasparatos et al., 2013). About 37% of corn production in the United States and vegetable oil in the EU is devoted to the respective biofuels (Groth & Bentzen, 2013). The USA and Brazil produce 90% of the world’s ethanol, which is the most widely used transport biofuel (Fulton et al., 2004), and Germany alone produces half of the world’s biodiesel (Martinot, 2005).

Second-generation biofuels employ the use of non-edible lignocellulosic[4] crops as feedstock in energy production[5] (Lunnan, 1997; Ramirez, Brown, & Rainey, 2015). These primarily include non-edible plant biomass like sugarcane crop residues (bagasse) (Kosinkova et al., 2015b), firewood, perennial grass, and forest and plantation residues for biopetrol (O'Connell et al., 2007), and jatropha[6] for biodiesel (Carriquiry, Du, & Timilsina, 2011).

[4] Lignocellulosic biomass is plant biomass consisting of cellulose, hemicellulose, and lignin that can be processed to produce chemical compounds for biofuels.
[5] Second generation alternatives are also generally regarded as employing more efficient production technologies, at a higher cost, to produce more energy per unit biomass (Singh et al., 2011a). For this paper, more emphasis is given to the feedstock type than the production process in classification of biofuels given the additional aims of comparing the broader implications of feedstock cultivation for biofuels.
[6] Jatropha is a non-edible flowering plant whose seeds contain oil that can be converted into biodiesel.

2.2.2. Feasibility of conventional biofuels

In studies that have estimated the financial feasibility of biofuel production relative to fossil fuels, conventional biofuels generally have been marked with higher production costs and therefore, uncompetitive retail prices (Demirbas, 2008; Hill et al., 2006). For example, Hill et al. (2006) estimate that, in 2005, biodiesel from soybeans was about 20% more expensive to produce than the wholesale price of diesel, while ethanol was about 5% more expensive to produce than the wholesale gasoline price. The post-2005 increases in fossil fuel prices (by as much as 30%[7]) allowed for these biofuels to be increasingly competitive (Coyle, 2007; U.S. Department of Energy, 2014), but prices have generally remained in favour of fossil fuels (Demirbas, 2008). However, policy support through blending mandates[8] and tax credit policies have allowed some variants to enter the consumer fuel market, with sugarcane ethanol in Brazil being a prime example (Goldemberg & Guardabassi, 2009).

Market or production-based prices do not capture the potential non-market benefits associated with the production and consumption of biofuels. This results in an inefficient allocation of resources and a potential undersupply of biofuels, assuming net positive externalities from production and consumption. Accounting for these benefits, possibly through subsidies (Msangi et al., 2007), can result in the economically efficient quantity and price of biofuels. Theoretically, subsidies associated with biofuels (of any iteration) account for the external benefits of having a lower net environmental impact relative to fossil fuels (Hill et al., 2006; Wassell Jr & Dittmer, 2006), and benefits from increased fuel access and national/regional energy independence (de Fraiture, Giordano, & Liao, 2008; de Gorter & Just, 2010; Khanna, Ando, & Taheripour, 2008), known in economic terms as positive

[7] http://www.eia.gov/forecasts/steo/realprices/

[8] Blending mandates refer to legal requirements for a ratio of biofuels to regular fossil fuels (petrol or diesel) sold (de Gorter & Just, 2009).

externalities. However, consideration must be given to the assumptions of existence and actual value of these benefits, in particular those addressed below.

2.2.3. Energy return

Although the benefits of biofuels have been much elaborated in the literature, there are caveats that can undermine particular benefits. These are often due to energy-intensive production and current dependence on fossil fuels in the production and transport of the biofuels that can negate energy and GHG benefits (Cherubini et al., 2009; Ulgiati, 2001). Studies on the Energy Return on Investment (EROI), which measures the usable energy produced from the resulting biofuel divided by the energy used in production, have found less optimistic results for biofuels. Among biofuels, sugarcane ethanol and palm oil biodiesel were found to be the most energy efficient among their respective fuel types (de Vries, van de Ven, van Ittersum, & Giller, 2010; Gasparatos et al., 2012; Menichetti & Otto, 2009). These feedstocks were also found to be the most energy productive per area of cultivation. Conversely, corn ethanol and biodiesels from rapeseed and soybean were found to score low in energy productivity (de Vries et al., 2010; Panichelli, Dauriat, & Gnansounou, 2009; Rajagopal, Sexton, Roland-Holst, & Zilberman, 2007).

However, comparisons with fossil-based petrol and diesel suggest that the EROI of conventional biofuels are much lower than fossil-based petrol and diesel (Table 2.3). Corn ethanol, a major biofuel in the USA, was particularly low in the EROI scales (Ulgiati, 2001), with EROIs between 0.8 to 1.7 compared to fossil fuels at 10. Second-generation variants require marginally less energy (Whitaker, Ludley, Rowe, Taylor, & Howard, 2010) and represented the more promising option for ethanol from both an EROI view (with estimates up to 11) (Farrell et al., 2006; Sheehan et al., 2003; Solomon, 2010) as well as an energy return per area of cropland (by as much as five times higher than first-generation) (Rajagopal et al., 2007); the latter due to emphasis on fast-growing perennial crops that can produce up to 10 times more energy than other bioenergy outputs (Berndes, Hoogwijk, & van den Broek, 2003). This supports qualitative comparisons on energy return between the two generations of feedstocks (Scharlemann & Laurance, 2008). However, most second-generation feedstocks were found to have comparably low EROIs relative to fossil fuels.

Table 2.3: Energy return on energy invested (EROI) for fossil fuels and common biofuel feedstock.

Fuel type/feedstock	EROI†	Source
Fossil fuels (gasoline and diesel)	9 - 10	Cleveland (2005); D. J. Murphy and Hall (2010)
First generation ethanol		
• Corn	0.8 – 1.7	Stromberg and Gasparatos (2012)
• Corn	1.1	de Oliveira, Vaughan, and Rykiel (2005)
• Corn	1.5	Farrell et al. (2006); Pimentel and Patzek (2005)
• Wheat	1.6 – 5.8	Stromberg and Gasparatos (2012)
• Sugarcane	3.7	de Oliveira et al. (2005)
• Sugarcane	3.1 – 9.3	Stromberg and Gasparatos (2012)
• Sugarcane	4.4	Hammerschlag (2006)
Second-generation ethanol		
• Cellulosic ethanol	11	Farrell et al. (2006)
First generation biodiesel		
• Palm Oil	2.4 – 2.6	Stromberg and Gasparatos (2012)
• Soybean	3.7	Delucchi (2006); Hill et al. (2006),
• Soybean	1.0 – 3.2	Stromberg and Gasparatos (2012)
• Rapeseed	3.7	Solomon (2010)
Second generation biodiesel		
• Jatropha	1.4 - 4.7	Stromberg and Gasparatos (2012)

†EROI = (Usable energy acquired)/(Energy expended)

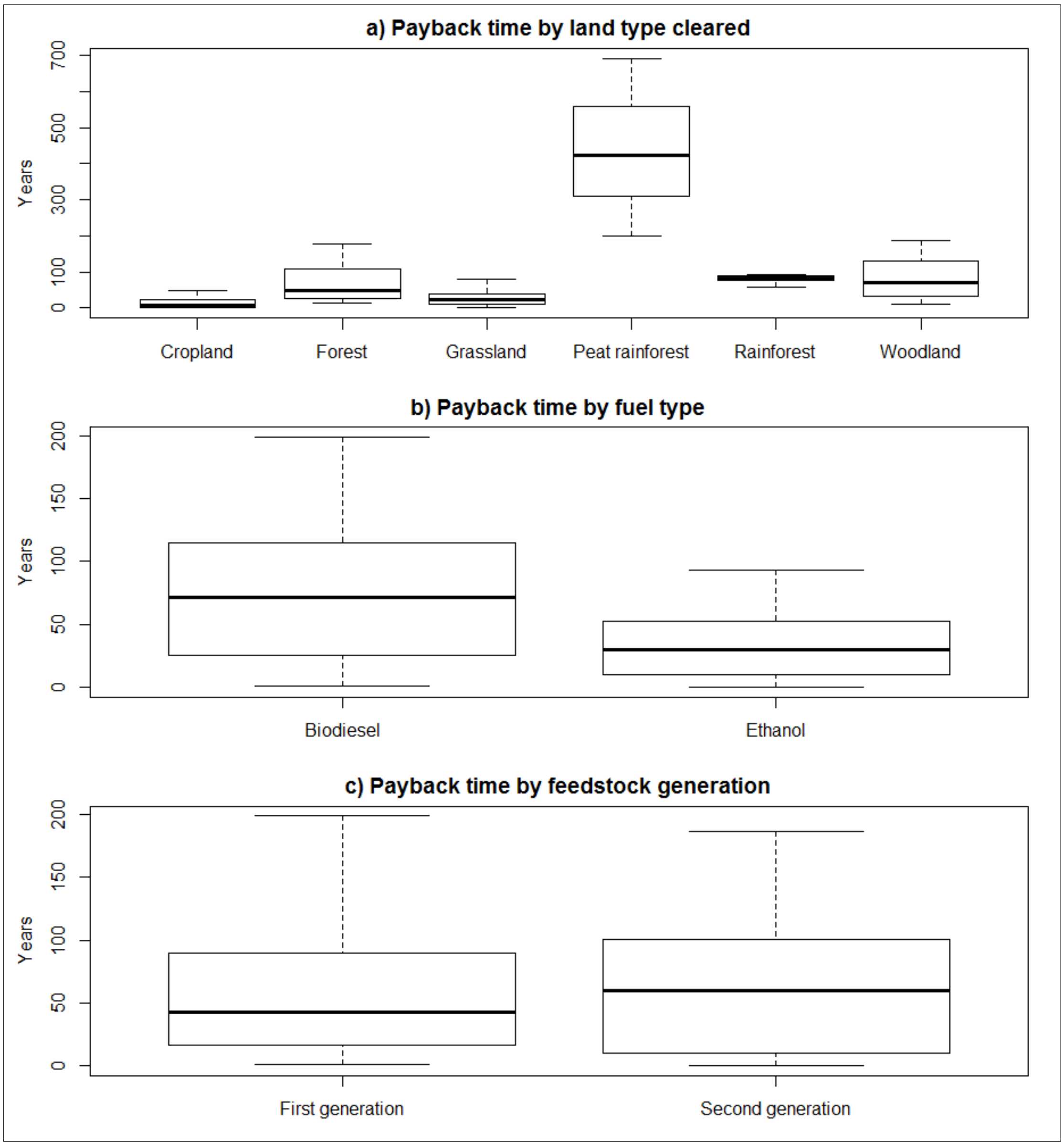
2.2.4. Net carbon benefit

A number of studies analysing the greenhouse gas (GHG) emissions of biofuels have suggested lower GHG emissions by up to 90% relative to fossil fuels (Farrell et al., 2006; Hill et al., 2006; Menichetti & Otto, 2009; O'Connell et al., 2007); with biodiesels generally having higher emission reduction. However, these studies have often not accounted for the effect of land-use changes resulting from increased biofuel crop cultivation that can offset these GHG benefits from production and consumption (Gallagher, 2008; Gasparatos et al., 2013). This is due to the loss of standing carbon sinks from land conversion for biofuel crop cultivation, particularly deforestation (Chung, Beardall, Mehta, Sahoo, & Stojkovic, 2011; L.

M. Curran et al., 2004; Lapola et al., 2010a; O'Connell et al., 2007). It is estimated that 17 to 420 times more carbon can be emitted from land clearing (Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008), which results in a substantial "payback" period for net emission reductions to be achieved (Figure 2.1).

Biodiesels in particular, such as those derived from palm oil in Southeast Asia (Achten & Verchot, 2011; Fargione et al., 2008) and Jatropha in Mozambique (Vang Rasmussen, Rasmussen, & Bech Bruun, 2012), have been found to have the highest relative carbon debt repayment time from loss of rainforests and woodlands respectively. Induced land changes from converting existing cropland have also been a source of indirect GHG costs (Achten & Verchot, 2011; Lapola et al., 2010a). The estimates modelled in Figure 2.1 also show that the type of land cleared and emissions on combustion (with biodiesel having greater emissions than ethanol) are more indicative of the net carbon benefit/cost than the type of feedstock that is cultivated for conventional biofuels.

Figure 2.1: Distribution of estimated carbon "payback" based on (a) type of land cleared, (b) type of biofuel produced, and (c) feedstock generation



Adapted from: Gasparatos et al. (2013)

2.2.5. Socio-economic benefits from energy independence

An advantage of biofuels is the ability to provide some level of energy independence that benefits society, particularly in developing communities. This includes reduced dependence on imports and increased fuel security (Rajagopal et al., 2007). This has been achieved through national-level policies in Brazil and at smaller community-levels in parts of Africa (Banda, 2009; Gasparatos et al., 2012), the latter exemplifying further benefits of selfsustaining fuel sources in rural, land-locked regions (Gasparatos et al., 2013). The ease of access to the fuel is an advantage to developing communities in terms of employment, productivity, commerce, and local-level trade. The associated employment opportunities can occur both at lower-skill levels, such as in agriculture, to higher-skilled levels such as research and development (e.g. engine innovations in Brazil) (Gasparatos et al., 2013).

However, subsidy policies for biofuels coupled with blending mandates to support biofuel production and increase demand have been shown to theoretically result in increased fossil fuel demand through the "green paradox" (Grafton et al., 2010; Kalkuhl et al., 2013). This occurs when increasing trends of policies enacted to encourage consumption of environmentally friendly or 'green' alternatives accelerates the use of 'non-green' resources by private producers looking to maximise returns. This may induce supply-side effects that may overcome the intended substitution effect of the original 'green' policy (Sinn, as cited in Grafton et al., 2010, p. 2)[9]. Works by de Gorter and Just (2007, 2009) similarly found that the ethanol tax credit policies enacted in the USA were counter-productive when implemented together with fuel mandates, which resulted in potential increased dependence on fossil fuel imports.

2.2.6. Impacts to food prices and agricultural resources

Increased conventional biofuel demand will result in opportunity costs from the reallocation of agricultural crops and resources (Prabhakar & Elder, 2009). This is due to the competition for these inputs with food production. Much of the feedstock cultivation at present is food-based and using scarce agricultural inputs (particularly land and water) (Msangi et al., 2007). Quantitative assessments have found biofuels have a greater impact on food prices than

[9] This paradox can be largely overcome by simultaneously imposing a tax on fossil fuel-based energy production. While a combined tax/subsidy program can provide welfare gains, a subsidy-only program is likely to result in welfare losses (Galinato & Yoder, 2010)

energy prices (Rajagopal et al., 2007), particularly with first-generation feedstocks (HLPE, 2013; Timilsina et al., 2011). Studies have found up to 40% of corn/maize price increases to be the result of ethanol mandates in the USA (Drabik, 2011; Mitchell, 2008; Rajagopal, 2008) and projection of increasing first-generation biofuel demand to result in increases in crop and livestock prices of between 5 to 15% (Fischer, Hizsnyik, Prieler, Shah, & Van Velthuizen, 2009). This reduces the affordability and supply of food, and exacerbates world hunger.

However, contradictory studies suggest that increases in food prices may be the result of other factors. The slow uptake of biofuels would not sufficiently increase the competition of agricultural resources to directly affect food prices (Ajanovic, 2011; Bastianin et al., 2013; Groth & Bentzen, 2013; Hochman, Rajagopal, & Zilberman, 2010, 2011) or have exhibited any long-run relationships with food prices (R. J. Myers, Johnson, Helmar, & Baumes, 2014). Some estimate the influence of biofuel production on food prices to be at a substantially less extent than originally estimated (Baffes & Haniotis, 2010; Baier, Clements, Griffiths, & Ihrig, 2009) or without causality (Bastianin et al., 2013). Increasing oil prices (McPhail, Du, & Muhammad, 2012), unpredictable weather patterns, demand from increasing populations, and most influentially, speculation (Baffes & Haniotis, 2010; Ghosh, 2010) have been suggested to be more consequential to rising food prices; by as much as 90% (Baier et al., 2009).

Impacts to land and water resources have been identified as a potential issue of increased biofuel demand (Kosinkova et al., 2015a). Trends in resource scarcity from increasing global population and limited arable land suggest the unsustainable nature of conventional biofuels (Batten & O'Connell, 2007; Chisti, 2008), which would result in a 44% increase in arable land demand by 2020 (Gallagher, 2008) but this would only meet a marginal proportion of fuel demand (Coyle, 2007; Goldemberg, 2007). Also, the resulting pressure on farmers to convert food crops to biofuel crops due to increased biofuel demand has already been noted to affect food prices (Ash & Dohlman, 2007; Bastianin et al., 2013). This demand for arable land has also been detrimental in the mass deforestations that have occurred in Southeast Asia for palm oil (Chung et al., 2011; Koh & Wilcove, 2008; O'Connell et al., 2007) and Brazil for sugarcane and soybeans (Lapola et al., 2010a; Lapola et al., 2010b); this results in losses of both carbon stores (see section 2.2.4) and ecosystem biodiversity (L. M. Curran et al., 2004; Fitzherbert et al., 2008; Germer & Sauerborn, 2008). Second-generation feedstocks have also been found to raise trade-off issues with regards to land for food and fodder, particularly in poorer rural communities (Escobar et al., 2009; Rajagopal, 2008).

Cultivation of terrestrial-based biofuel feedstocks is also water intensive. This results in trade-off issues with regards to water allocation. Estimates for water requirements have been found to be undervalued to the point of being higher than natural replenishment rates from aquifers both in USA (Chiu, Walseth, & Suh, 2009; Pimentel, 2003) and Brazil (de Oliveira et al., 2005; Rajagopal, 2008). Specific feedstocks have been identified as being particularly water-intensive, such as sugarcane (molasses) (de Oliveira et al., 2005) and palm oil (Rajagopal, 2008). Despite requiring relatively less water resources (Carriquiry et al., 2011), second generation crops can face a trade-off with productivity and biomass output (Rajagopal, 2008).

Currently, the actual impacts from increased biofuel use in a market to food prices are complex to quantify. This is due to the multiple sources of impacts, namely direct competition for crops and indirectly through competition for agricultural resources. Also, biofuels do not represent a major market alternative in most countries, making it difficult to establish strong, quantifiable links. Further research is required to fill this gap but it is likely to only be motivated through increased market penetration of agricultural-based biofuels. However, the points mentioned in this section can form reasonable presumptions that increased biofuel production from conventional feedstocks will have some impact on food prices.

2.3. Algae-based biofuels

The development of third-generation, algae-based biofuels have been highlighted to address many of the above issues (Stephens et al., 2010), in particular, the impacts associated with food production from both feedstock and resource competition for both arable land and water (Singh et al., 2011a).

Considerable attention over the last decade has focused on the potential for algae as a biofuel feedstock. The sugars in marine macroalgae, such as seaweed, have been found to be suitable for bioethanol production (John, Anisha, Nampoothiri, & Pandey, 2011; Wei, Quarterman, & Jin, 2013). Additionally, biodiesel from macroalgae is also feasible (Maceiras, Rodríguez, Cancela, Urréjola, & Sánchez, 2011). However, the higher growth and lipid accumulation capacities of microalgae (S. A. Scott et al., 2010) and the higher energy content in biodiesel compared to ethanol (by as much as 34%) (Chisti, 2008) has stimulated a greater research interest in the production of microalgae-based biodiesels. The high production efficiencies of microalgae biofuels have been also been suggested to provide greater fuel security for current and future fuel demands (S. A. Scott et al., 2010; Sheehan, Dunahay, Benemann, & Roessler, 1998), warranting policy investment in USA (A. Scott & Bryner, 2006).

Microalgae[10] is intensively cultivated[11] in controlled environments, commonly open ponds or closed plastic tubes known as Photo-bioreactors (PBRs), and in a nutrient and carbon dioxide (CO_2)-rich growth medium (Chisti, 2007). The cultivated algae biomass is then processed in a similar way as other lipid-based feedstock (transesterification[12]) to produce biodiesel. The carbohydrates in the cells can also be fermented to produce ethanol.

There are specific aspects to microalgae biodiesel production that can determine the feasibility and long-term viability of microalgae from a production standpoint; through the cultivation (Jorquera, Kiperstok, Sales, Embiruçu, & Ghirardi, 2010; Stephenson et al., 2010), harvesting (Molina Grima, Belarbi, Acién Fernández, Robles Medina, & Chisti, 2003; Sander & Murthy, 2010), lipid extraction (Batten et al., 2013), and transesterification. Studies by Brentner et al. (2011) and Stephenson et al. (2010) provide an indication to the different pathways at each stage of the process, which can determine the biomass/biodiesel output as well as the final cost per unit. The specifics to these processes will only be addressed as they pertain to various issues, implications, and externalities[13].

2.3.1. Financial feasibility

As with most first and second-generation biofuels, which are generally uncompetitive in the absence of subsidies, microalgae biofuels are not currently competitive with fossil fuels (Davis et al., 2011). However, they may be viable as potential aviation fuels given their compact energy properties (Norsker et al., 2011), and have been of interest at pilot scales for

[10] While some studies (e.g. Carriquiry et al. (2011)) categorize microalgae as a second-generation feedstock, this paper follows definitions by Dragone et al. (2010), Singh et al. (2011b), and Singh et al. (2011a) who specify third-generation biofuels attributing from organisms.

[11] Microalgae can be cultivated in extensive systems that are less technologically advanced but more land intensive (Darzins et al., 2010). Extensive cultivation has not been as efficient in productivity and is less favourable in recent microalgae literature, and thus, focus is given to intensive cultivation systems for this thesis.

[12] Transesterification is a chemical conversion of the lipid (fat) compounds into a biofuel compound.

[13] There are a number of alternative reviews for the production processes of microalgae biodiesel from an engineering perspective (e.g. Mata, Martins, & Caetano, 2010; Singh, Pant, Olsen, & Nigam, 2012), including those that describe potential improvements in the strain and processing of the microalgae to improve its viability (S. A. Scott et al., 2010).

airline companies (APAC Biofuel Consultants, 2013). Furthermore, research has indicated potential improvements to both cultivation (Davis et al., 2011) and processing (Pokoo-Aikins et al., 2010), with the latter focusing on reducing capital costs through lower-cost machinery specifically designed for processing microalgae (Davis et al., 2011; Slade & Bauen, 2013). Substantial reductions in costs can also be achieved if CO_2, nutrients, and water can be obtained at lower costs (Slade & Bauen, 2013) or recycled within production (Darzins et al., 2010). Appropriate supplies of CO_2, nutrients, and water in particular, are believed to be a limiting factor in the feasible production of microalgae (Pate, Klise, & Wu, 2011). However, with current production being limited to smaller research and development projects, the feasibility of these ideas in commercial production has not been investigated.

Microalgae production also has the potential to generate other commercially valuable by-products. Lipids (to be converted to biodiesel) only make up around 30% of the harvested biomass, with the remainder of the biomass being potentially useful as animal feed (Alam et al., 2012) or other energy-related products such as ethanol (Sander & Murthy, 2010), bio-gas (Odlare et al., 2011), or even hydrogen (Kruse & Hankamer, 2010) that can be used for fuel. The opportunity to produce high-value co-products from residual biomasses is a commercial benefit of microalgae over conventional biofuel feedstocks. Future commercial viability of microalgae as a biofuel may also depend upon appropriate commercial use of these co-products (Alam et al., 2012; Slade & Bauen, 2013). The experimental production of various co-products with biofuel production from microalgae (together with bio-fixation benefits) has been well documented in the literature over the past five years (Table 2.4).

Table 2.4: Recent studies of microalgae lipid-based fuels with co-products and/or external benefits.

Primary output	Alternative/co-product	External benefit(s)‡	References
Biodiesel	Methane	CS	P. K. Campbell et al. (2009); (P. K. Campbell et al., 2011)
		WT	Lardon et al. (2009)
	Non-specific co-product value		Darzins et al. (2010)
	Glycerol	CS	Pokoo-Aikins et al. (2010)
	Ethanol	WT	Sander and Murthy (2010)
		CS	Stephenson et al. (2010)
	Biogas		Brentner et al. (2011)
		CS, WT	Frank, Han, Palou-Rivera, Elgowainy, and Wang (2011)
Algae oil/ oil-based fuel	Ethanol	CS, WT	Alabi, Tampier, and Bibeau (2009)
	Biogas	CS, WT	Lundquist, Woertz, Quinn, and Benemann (2010)
	Biogas, Stockfeed	WT	Batten et al. (2013)

‡CS = carbon sequestration of flue gas, WT = wastewater treatment

2.3.2. Energy requirements

Relative to terrestrial feedstock, microalgae has a substantial energy requirement from the various machinery and capital inputs of the accelerated cultivation cycles (Clarens et al., 2010). This results in lower net energy returns from conversion compared to conventional biofuels, which make it uncompetitive and even unsustainable (Lardon et al., 2009; Sander & Murthy, 2010). This substantial energy demand can potentially result in a net energy loss from conversion to microalgae biodiesel, or at best a marginal gain, given the current technologies (S. A. Scott et al., 2010).

Comparing open-pond and PBRs, the former is most often found to have a more efficient EROI. An exception was Sander and Murthy (2010) who found higher value estimates for open-ponds. Open-ponds were also found to have less energy intensive cultivation, with more significant energy costs being incurred from the harvesting and drying stages of production, adding as much as 10 times to the energy ratio (Kadam, 2002; Lardon et al., 2009; Slade & Bauen, 2013).

In contrast, the more controlled environments associated with PBRs resulted in significantly higher energy costs for cultivation, and a lower energy ratio/EROI. The majority of energy costs were attributed to construction and culture circulation (Jorquera et al., 2010; Stephenson et al., 2010). This has led to questions on the viability of PBRs in relation to their high energy input requirements given current technologies (Hulatt & Thomas, 2011).

However, as the industry is relatively new, there is potential for improvements in the algae strain and production technology that could ensure a higher probability of positive net energy balance, though it is an area requiring further research.

2.3.3. Net carbon benefits

Microalgae, like terrestrial agriculture, converts carbon dioxide into biomass via photosynthesis (Chisti, 2007). While this process has been shown to occur more efficiently in microalgae than with other feedstocks in terms of area farmed (Rosenberg, Mathias, Korth, Betenbaugh, & Oyler, 2011; Wang, Li, Wu, & Lan, 2008), conversion is still relatively expensive. Ono and Cuello (2003) estimated the net unit cost of carbon mitigation using microalgae production with a solar collector at US$100 per ton carbon dioxide. They stressed the importance of producing commercially viable outputs to lower net costs.

Commercial microalgae production is also expected to have positive net carbon emissions, unlike its terrestrial counterparts, due to the controlled production environment, particularly for PBRs (Slade & Bauen, 2013), and related machinery that require electricity derived from fossil fuels (P. K. Campbell et al., 2011; Clarens et al., 2010). Additionally, the use of fossil fuels in the downstream processing of the biomass can also possibly counteract the carbon sequestration benefits achieved in the upstream cultivation, as with conventional biofuels (Brennan & Owende, 2010; Xu, Brilman, Withag, Brem, & Kersten, 2011).

The recycling of flue gas from power plants in the cultivation process has also been suggested to yield a net reduction in carbon emissions. The flue gas can be sparged[14] into the growth medium of the microalgae as the input of carbon dioxide, adding benefits of more efficient carbon bio-fixation (Kadam, 1997; Mata et al., 2010) without affecting the biomass growth (Negoro et al., 1993). Some experimental and application studies on the efficiency of a microalgae species to employ a high-concentration flue gas (sometimes simulated) supply, demonstrated the feasibility and efficiency of this application beyond terrestrial agriculture (Iwasaki, Hu, Kurano, & Miyachi, 1998; Sakai, Sakamoto, Kishimoto, Chihara, & Karube, 1995; Wang et al., 2008; Zeiler, Heacox, Toon, Kadam, & Brown, 1995). Despite this sequestration benefit, the net CO_2 benefit from microalgae is dependent on the emissions from subsequent use of the biomass as a fuel. Assuming the CO_2 assimilated is emitted on combustion; the net emissions' schedule will depend on the energy intensity of the biomass processing that may require fossil fuels (Mata et al., 2010).

2.3.4. Nitrogen benefits

Microalgae cultivation requires nutrients within the growth medium, primarily nitrogen (Chisti, 2007; Mata et al., 2010). This presents an opportunity for the use of microalgae in removing high concentrations of nitrate compounds in runoff of wastewater, a major cause of eutrophication[15] (Pittman, Dean, & Osundeko, 2011). In addition to its high nitrogen sequestration efficiency (Woertz, Feffer, Lundquist, & Nelson, 2009), microalgae cultivation also represents a cost-effective and low chemical-based method for wastewater treatment, assuming it is presented with adequate growth conditions. Batten et al. (2013) were able to show that with wastewater treatment as a primary objective, microalgae biodiesel was able to be produced at less than US$1 a litre, assuming a waste carbon dioxide source, and water and

[14] Sparging is a technical term for bubbling gas into a liquid.
[15] Eutrophication occurs when the leakage of fertilisers into bodies of water (e.g. lakes, rivers) cause the excessive growth of aquatic plants (e.g. algae, photoplankton) resulting in competition for space, sunlight, and oxygen among other marine organisms.

nutrients were recycled in the algae ponds. However, a wastewater-based cultivation medium may restrict the potential of biofuel production, as there is an inverse relationship between nitrogen saturation in the growth conditions and production of lipids (the essential element for biofuel production) (Lardon et al., 2009; Williams & Laurens, 2010).

2.3.5. Benefits for food security and resource competition

Assuming trends for increased policy support for transport biofuels, microalgae as a feedstock can alleviate some pressure that first and second-generation biofuels have on food security. Although there is the potential for some microalgae strains as supplements in the human diet (Mata et al., 2010), it currently does not form a widespread dietary choice. Hence, as with second-generation feedstocks, microalgae biomass would not have an opportunity cost for food supply[16] (Rajagopal, 2008). Microalgae cultivation also reduces competition for water, given that it is preferably cultivated in wastewater (Woertz et al., 2009), although as previously mentioned, the high nutrient saturation can be consequential to the feasibility of its production for relevant outputs (Lardon et al., 2009; Williams & Laurens, 2010).

Similarly, with emphasis on shifting feedstock cultivation away from agricultural land (Gallagher, 2008), microalgae can reduce the opportunity costs associated with scarce land resources devoted to energy crops. Microalgae cultivation does not have a similar demand for arable land (marginal or otherwise) as comparable terrestrial biomass (Ahmad, Yasin, Derek, & Lim, 2011) given that it can be cultivated in artificial environments (Chisti, 2007). Overall, algae cultivation for biofuels can potentially have a minimal effect on food security and a transition to this feedstock may potentially alleviate pressure on conventional feedstock-related impacts on food and agricultural resources as discussed previously.

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[16] In contrast, most macroalgae production is currently used for food, suggesting that diversion to biofuels may impact food supplies.

Furthermore, the reduced demand for arable land negates the need for widespread conversion of forests and woodlands. This reduces potential impacts on carbon sink and biodiversity loss (Groom, Gray, & Townsend, 2008), which have plagued conventional feedstocks (Mata et al., 2010).

2.3.6. Socio-economic benefits

The development of microalgae biofuel industries also presents a number of socio-economic benefits that may contribute to a socially sustainable outcome. Social sustainability involves, amongst other aspects, the potential for a more equitable distribution of economic benefits across society, including regional and urban communities (Khanna, Hochman, Rajagopal, Sexton, & Zilberman, 2009), and improvements in the quality of life. The most obvious of these benefits is the establishment of an energy industry that can sustain longer-term fuel demands, as well as generate employment, and economic growth in rural communities. This is in contrast to existing fossil-based industries that are dependent on finite resources and conventional biofuels that are restricted by resource limitations (Sheehan, 2009). As a long-term sustainable industry, microalgae biofuel production can also provide outlets for growth of related jobs across skill-levels, similar to those associated with conventional biofuels (Gasparatos et al., 2013).

Microalgae-based industries also present an opportunity for economic growth in non-metropolitan and regional areas. Public and private investment of bioenergy projects are often centred on employment and income opportunities for businesses and local communities, particularly in regional areas (Domac, Richards, & Risovic, 2005). It has been suggested that there are significant opportunities for sustained growth of agricultural industries and incomes through conventional biofuels (Anuar & Abdullah, 2016). However, in many instances it would be difficult to justify policy support for conventional biofuel production given its impacts to broader society in terms of higher food prices and resource constraints. In contrast, the cultivation of microalgae, integrated with existing complementary industries, might present a superior alternative. In addition to supplementing the incomes of seasonal industries, the synergy from bio-fixation of waste effluents and production of usable co-products (e.g. feed, fertiliser) (Alam et al., 2012) may prove economically beneficial to local communities.

2.4. Discussion

There is a need for further development in biomass-based fuels given the current dependence on liquid fuels for transportation and the finite nature of fossil fuels that dominate the market. To date, most attention has been given to terrestrial-based feedstock and related production systems. The external benefits of such systems initially looked promising, receiving policy support to reflect the perceived non-market benefits (e.g. in the USA and Brazil) (Gasparatos et al., 2013). However, the literature has indicated that these benefits may be overstated. In particular, there is growing evidence that land clearing for crop production, particularly in tropical regions, may result in a net increase in greenhouse gases through the loss of substantial carbon sinks.

As summarised in Table 2.5, the overall social and economic benefits from conventional biofuels are also uncertain due to the impact on food prices and supply, and the induced loss in non-market ecosystem services through land clearing/conversion. The welfare effects of these changes are complex. The potential for additional employment and income generated through crop-based biofuel production, and improved fuel access, may offset the higher food prices, especially in poorer regions. Similarly, higher food prices can result in improved incomes for farmers, many of whom are also often in low-income groups. However, given that the benefits of the feedstock cultivation may not be shared efficiently across the society, the distribution of gains between net producers and net consumers of agricultural commodities is an empirical question that must be answered in order to understand the overall impacts on human welfare (M. Ewing & Msangi, 2009).

Algae, particularly microalgae, offers a new potential for biofuels that does not appear to have the same level of associated negative externalities from production. As with most biomass-based biofuels, microalgae biodiesel is currently unable to compete with fossil fuels in terms of price, although this is potentially due to the relative infancy of the production and processing technology (S. A. Scott et al., 2010). Aside from the potential for technological improvements that would reduce production costs, there is also a potential for the biomass to be allocated to other output products and possibly improve the financial feasibility. However, there has currently not been any analysis into an output allocation of feasible biofuel production for a conclusion to be made on the viability of microalgae cultivation for biofuels.

An additional drawback of microalgae cultivation and processing is that they are capital and resource intensive. Aside from the construction and maintenance of the artificial environments, there are substantial requirements for energy, water, and related nutrients for the facility to be able to produce sufficient biomass (Clarens et al., 2010). Although there are opportunities to recycle waste resources as production inputs (Yang et al., 2011), the high energy requirements suggest the dependence on fossil fuel energy, at least in the short to medium-term, to sustain the various downstream processes (Xu et al., 2011).

Despite these issues, the positive externalities of microalgae biofuels illustrate potential welfare benefits for society. In addition to the environmental benefits, algae-based technologies overcome issues with resource competition, which can affect both food prices and biodiversity. Furthermore, these technologies can contribute to social sustainability through employment and income generation, particularly for regional communities that are typically dependent on seasonal industries.

The development of conventional biofuels has largely benefited from various policy interventions. These include directly supportive measures; such as tax concessions, reduced fuel excises (de Gorter & Just, 2009), and subsidies for production and infrastructure (Batten & O'Connell, 2007); or indirect measures; like biofuel blending mandates and trade measures protecting domestic biofuel industries from lower-cost foreign suppliers (OECD, 2008). Such measures were estimated to have cost US$11 billion in 2006 and forecasted to be US$25 billion in 2017 (OECD, 2008).

The implementation of relevant policy mechanisms to reflect the economically efficient price can improve feasibility of production and its viability as a longer-term and sustainable alternative to fossil fuels (Lee, 2011). The relative rapid growth in terrestrial feedstock (e.g. in Brazil) demonstrates that producers and consumers respond to incentives provided under such policies. However, this review has identified various economic costs of conventional biofuels that suggest inefficiency in policy support in developing these industries.

While these policies could be applied to microalgae production, the higher start-up costs and risks provide an additional disincentive to invest in the industry compared to the lower-cost agricultural-based production. Finding a policy mix that provides appropriate incentives for third-generation biofuels, whilst transitioning away from conventional approaches and managing the associated risks, is likely to be as big a challenge, with the technological developments required to justify these incentives and the feasibility of the fuel. However, the potential of microalgae biofuels to meet fuel demands with greater net external benefits than conventional biofuels warrants consideration and research.

2.5. Conclusion

The aims of this review were to investigate the economic issues surrounding conventional biofuels, and highlight the key economic benefits of microalgae biofuels over its conventional predecessors.

Key limitations were identified for conventional biofuels, particularly in the food versus fuel debate, suggesting the need for developing alternative feedstocks. Microalgae is itself impeded by high production and energy costs, despite being found to alleviate much of the shortcomings that plague its predecessors. Policy intervention, a major influence on the development and use of conventional biofuels, was suggested for microalgae biofuels based on long-term needs for a transport fuel substitute that does not raise environmental and socio-economic costs on society.

These findings will inform the following studies in this thesis, with each addressing the financial (Aims 2 and 3), socio-economic (Aim 4), and policy aspects (Aim 5) of microalgae biofuels.

Table 2.5: Key economic benefits and limitations for first, second, and third generation biofuels for policy consideration§.

Biofuel type	Benefits	Limitations
First generation	Policy support has shown spillover benefits to other sectors of the economy (2.2.5)	Low EROIs (2.2.3)
	Cheaper production costs allow poorer communities to have access to renewable source of transport fuel (2.2.5)	Potential high emissions from land conversion (2.2.4)
	Benefits to lower-income farming communities particularly in developing countries (2.2.5)	Loss of biodiversity from land clearing/conversion (2.2.6)
		Competition for crop allocation for food (2.2.6)
		Competition for agricultural resources (2.2.6)
Second generation	Higher EROIs than first-generation (2.2.3)	Can raise pressure to convert existing forestland/cropland (2.2.6)
	Less pressure on crop/agricultural resource demand compared to first generation (2.2.6)	Competition for agricultural resources (2.2.6)
		Insufficient supply if dependent on residual/waste biomass (2.2.6)
Third generation	Utilises waste effluents in cultivation; carbon sequestration (2.3.3), wastewater treatment benefits (2.3.4)	Infant technology, high costs and estimated prices (2.3.1)
	Can be cultivated on marginal/non-arable land (2.3.5)	Energy intensive nature of harvesting and processing (2.3.2)
	Potential for high value co-products (2.3.1)	Dependence on fossil fuels in production stages raises environmental costs (2.3.3)
	Reduces impacts to biodiversity (2.3.5)	
	Potential development of long-term industry, employment, and economic growth (2.3.6)	
	Social sustainability for regional communities (2.3.6)	

§Numbers in brackets correspond to section of the review.

Chapter 3. Techno-economic analysis of microalgae biodiesel production

3.1. Introduction

Production-based models are common for studies on biomass production and biofuels in the chemical/process engineering discipline. Process engineers model a production system (hypothetical, experimental, or commercial) to determine various indicators of feasibility. This can include more technical aspects like mass, heat or energy requirements, or simple financial parameters such as net present value (NPV) and financial sensitivity. These models also allow for capturing changes in production scales or aspects of the production system, and illustrate these effects in the final feasibility metrics. The scope of production-based financial models, also known as techno-economic models, in the context of microalgae biofuels, has included sensitivity analysis of single production cycles (Sánchez, Ojeda, El-Halwagi, & Kafarov, 2011) and derivation of an NPV to gauge the financial feasibility of the production system through a longer-term investment (Zamalloa, Vulsteke, Albrecht, & Verstraete, 2011). These models help to steer research and development, particularly for infant industries like microalgae biofuels, to improve financial feasibility (Borowitzka, 2013).

The aim for techno-economic models in microalgae has often been based on technical aspects, such as changes to cultivation systems (Davis et al., 2011) or production processes (Taylor et al., 2013). These objectives have allowed for estimation of the fuel price, which provides an indication on the financial feasibility of the production process and the likelihood of microalgae biofuels being introduced into the current biofuel market. These studies have often suggested that current technologies are not sufficiently developed to warrant commercial competitiveness, although opportunities have been suggested for technological developments and multi-output production systems (Taylor et al., 2013).

The aim of this study was to assess the feasibility of a multi-output production system through a techno-economic analysis (TEA). Also, this study evaluated microalgae biofuel production integrated with complementary industries using waste effluents as cultivation inputs, with the potential to reduce costs and provide bio-mitigation benefits. The selection of output products apart from biofuels also considered the benefits to the integrated industries, namely agriculture and aquaculture. The baseline results were then tested with sensitivity and switch value analyses to determine the impact of various parameters on the feasibility of the production system. The findings from these analyses illustrate the potential of microalgae production in an integrated production system and with multiple outputs. These findings will prove consequential to producers in both microalgae and complementary industries, and to decision makers considering the viability of microalgae biofuels.

The next section will present a brief review of the microalgae production literature including the various output products that can be produced from the resulting biomass. Following this, the methods used in the techno-economic model will be outlined, covering the framework, parameters, and a description of the financial valuation methods. Then, the results from the financial and sensitivity analysis will be detailed. Finally, a discussion will be presented covering the implications of the findings, limitations of the study, and opportunities for further expansion of this techno-economic model.

3.2. Review of microalgae production

More commonly used in the engineering discipline, the more complex aspects of the TEA involve defining and modelling the production processes based on available technologies and assumptions. This section discusses the literature pertaining to microalgae production, particularly the various processes and potential outputs from the biomass.

3.2.1. Early research into microalgae production

Research into the potential of microalgae biomass to meet commercial demands for a source of proteins and other associated compounds has been carried out since the 1950s, with Spoehr (1949) and Cook (1950) investigating the intensive cultivation of Chlorella under various environmental conditions. This subsequently stimulated an interest in larger-scale autotrophic (cells that produce their own food) production, as covered in reviews by Goldman (1979), and Tapie and Bernard (1988). Increasing fuel prices encouraged research into microalgae as a source of biofuels, particularly biodiesel, with the more seminal research for commercial production being conducted by Benemann, Goebel, Weissman, and Augenstein (1982), and Regan and Gartside (1983). Given that the specifics and assumptions of production varied across these models, early estimates varied greatly and resulted in a lack of consensus on both technical and financial feasibility of the technology at that time (Tapie & Bernard, 1988).

A report by Benemann and Oswald (1996) was a pivotal review in production feasibility for microalgae cultivation (for biodiesel). This report presented a technically efficient production pathway through carbon dioxide sequestration and wastewater treatment, based on a review on the various cultivation, harvesting, and processing technologies covered in the literature up to that point. Their study, although drawing a hypothetical pathway, attempted to estimate costs based on technological and financial developments, together with relevant justifications. While previous literature limited their scope to single process pathways, this report outlined multiple production options and financial feasibility of microalgae biodiesel. However, they did not attempt to estimate the outcome with concurrent alternative outputs.

They emphasized the need for further research to reach financial feasibility and competitiveness with fossil fuels, particularly with respect to benefits associated with carbon dioxide mitigation and other external benefits.

3.2.2. Scope of production process

In this review, the production process is divided into two distinct stages: 1) microalgae biomass cultivation and 2) output production from harvested biomass. The existing literature addresses various aspects of the production pathway. In particular, science and engineering literature regularly highlights developments in available technology for each stage. Given that the scope of this study is based on factors outside of these developments, discussion of the literature pertaining to the production system will be based on the following areas:

1) Cultivation stage
   a. Choice of cultivation system (open-pond versus photo-bioreactor)
   b. Potential for positive externalities through nutrient inputs
2) Output production stage: uses of biomass

3.2.2.1. Choice of cultivation system

The choice of the cultivation system to be used in the modelling is fundamental, particularly for hypothetical modelling, as it determines a substantial subsection of the capital and operating costs. Early research on microalgae focused primarily on cultivation at experimental scale and hence, employed relatively simpler methodologies (i.e. J. Myers & Graham, 1959; Spoehr, 1949). Goldman (1979) noted that there was an increasing interest in experimental mass culture systems post-WWII, with few being commercially viable. More recently, autotrophic, or more specifically, phototrophic (produces own food from sunlight) microalgae is either cultivated in open raceway ponds or closed tubular photo-bioreactors (PBRs)[17] (Chisti, 2007). The former was developed initially by researchers from the

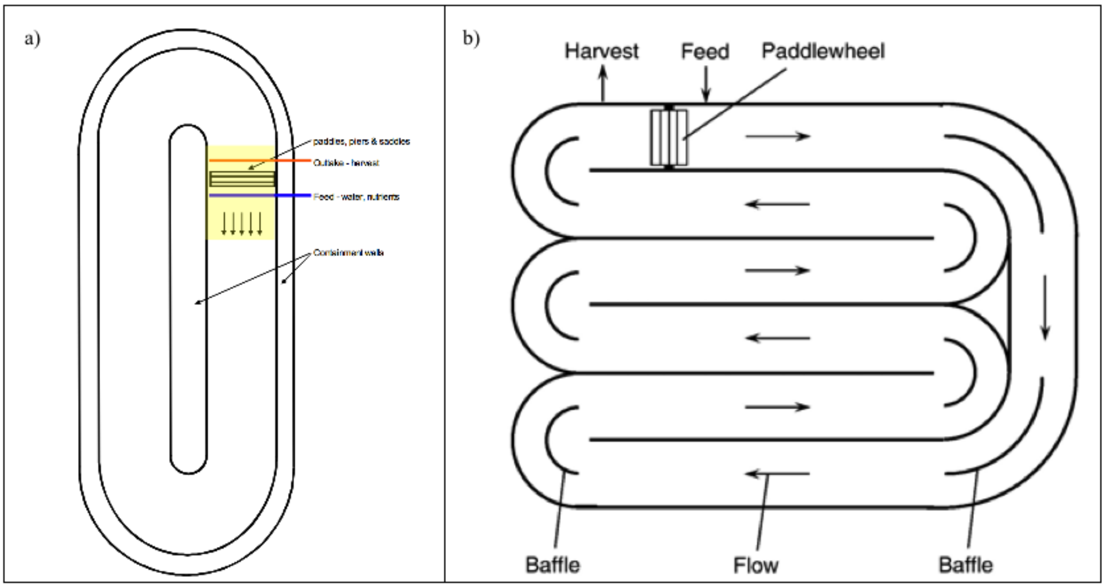
[17] The methods described focus on intensive methodologies over the relatively lower costing extensive methodologies.

University of California, Berkley, based on studies of experimental mass culture of algae (Oswald et al., 1957; Oswald, Gotaas, Ludwig, & Lynch, 1953). Subsequent research in Germany produced the raceway open-pond set-up (Stengel, 1970; Stengel & Soeder, 1975), which was then implemented in an experimental mass scale in Thailand (Soeder, 1976) and supported similar research in Israel (Shelef, Schwarz, & Schechter, 1973)[18]. A variant of the open-pond system was also detailed in the seminal reports by Benemann (i.e. Benemann et al., 1982; Benemann & Oswald, 1996), where the biomass was specified to be used for biofuels.

These open ponds consist of raceways with the water, sparged with carbon dioxide, and culture in the ponds already containing the relevant nutrients, are agitated by a paddlewheel. The pond is shallow and exposed to the sun for photosynthesis, leaving it vulnerable to excessive evaporation, resulting in greater water demands (Brentner et al., 2011). The designs for the open ponds are generally similar to those in outlined in Darzins et al. (2010) (Figure 3.1a), with variations in size and number of looping, interconnected raceways (e.g. Chisti, 2007; Darzins et al., 2010) (Figure 3.1b). There have been some studies into having the raceways covered with a transparent dome to reduce exposure to the elements and hence, minimize risk to the cultivation through contamination, although these have been performed only at an experimental level (Rosenberg et al., 2011). Despite having lower capital and operating costs than PBRs, commercial cultivation and biofuel production is still technically and financially unfeasible based on current phycology and production technologies (P. K. Campbell et al., 2009).

[18] See Goldman (1979) for a more in depth review of early mass microalgae cultivation.

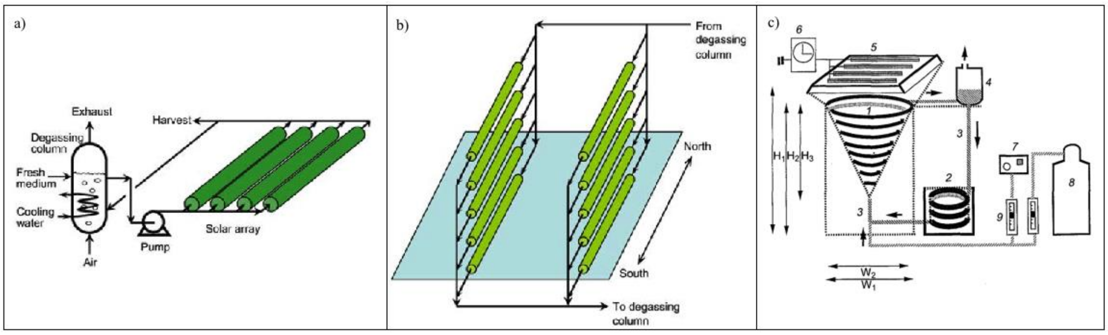
Figure 3.1: Diagrammatic examples of open-pond systems



Source: a) Darzins et al. (2010, p. 30), b) Chisti (2007, p. 297)

The more advanced PBR system was developed initially at an experimental stage in the 1970s through research with British Petroleum (as cited in Tapie & Bernard, 1988, p. 874). The work by Tapie and Bernard (1988) was among the first to report modelling of a PBR system to produce microalgae biomass. In a PBR, the algae culture and nutrients are circulated through transparent 'serpentine' plastic or glass tubes, exposed to the sunlight, and sparged with carbon dioxide (Tredici, 2003). This allows for more control over temperature, reduces probability of contamination, and potentially allows for greater surface exposure to sunlight. Studies have suggested that the relatively higher productivity can be explained by the surrounding temperature, with PBRs being more consistent in terms of growth patterns in less favourable climates (Rosenberg et al., 2011; Tredici, 1992). The variation of PBR geometry in more recent studies includes the basic flat and horizontal (Molina Grima, Fernández, García Camacho, & Chisti, 1999; Sánchez Mirón, Contreras Gómez, García Camacho, Molina Grima, & Chisti, 1999) (Figure 3.2a), vertical 'bio-fences' (Muller-Feuga et al., 2012; Tredici, 1999) (Figure 3.2b), and vertical coils i.e. helical tubular PBRs (Briassoulis et al., 2010; Watanabe, 1996) (Figure 3.2c).

Figure 3.2: Diagrammatic examples of PBRs



Source: a) & b) Chisti (2007, p. 298), c) Watanabe (1996, p. 694)

Despite the benefits of being able to control the culture environment, reduce evaporation loss, and realise faster growth rates, there are significantly higher capital costs. PBRs are a more complex newer technology and require more materials to be made (Davis et al., 2011; Jorquera et al., 2010; Tredici, 2003), resulting in financial infeasibility (Darzins et al., 2010). Benemann (2008), and Wang et al. (2008), also report against the perception that PBRs are more technically productive with the same resources, based on experimental results and the lack of success of smaller-scale commercial PBR facilities relative to open ponds, despite the focus on higher-value products.

Richardson et al. (2012) suggest that despite the technological developments and distinct characteristics of each method, there have been limited production-economics studies comparing the two methods to cultivate the biomass. Some studies that attempt to address the two systems often do so in a generalised manner (Chisti, 2007; Shen, 2009). These studies suggest that PBRs would have a higher productivity rate due to the greater control afforded in the closed tubular environment. Jorquera et al. (2010) demonstrated a life-cycle TEA comparing open ponds and PBRs, and expectedly found a higher energy ratio for PBRs under similar production output variables. Davis et al. (2011) compared a similar output target for the two systems. Although based on hypothetical facilities and dependent on various cost assumptions, their study confirmed the relative differences between the two systems, with PBRs being more productive, but at higher capital and operating costs, and power demands; these findings have been supported in some literature (Brentner et al., 2011; Stephenson et al., 2010), but contradicted in other literature (Alabi et al., 2009). The resulting biodiesel cost was almost twice for PBRs.

Earlier work suggests that PBRs also have higher and less sustainable energy requirements and net emissions than open ponds (Stephenson et al., 2010), although this was contradicted by Brentner et al. (2011). This is potentially a factor for commercial algae biomass producers, who generally opt for some variant of the open ponds over PBRs (Christenson & Sims, 2011). However, findings from Norsker et al. (2011) suggested that taking into account the biomass and energy output, there is little consistent difference in cost per mass or per unit energy of the microalgae biomass between the PBR and open-pond systems[19]. These findings had made conservative assumptions on the initial capital expenditure of the PBR systems as compared to other comparative studies (e.g. Davis et al., 2011).

3.2.2.2. Potential for positive externalities through nutrient inputs

Much of the economic literature of microalgae production has been conducted with the purpose of testing its technical and financial feasibility. There have been attempts to include external benefits of microalgae cultivation through factoring input benefits of carbon sequestration from flue gas, and wastewater-nitrogen bio-fixation, both of which would have otherwise been disposed into the environment. Benemann and Oswald (1996) were among the earliest to suggest the potential for feasible production and concurrent bio-fixation. In this

[19] A study by Huntley and Redalje (2007) demonstrated a hybrid open-pond and PBR system used to cultivate microalgae for carbon dioxide mitigation and had been successful for four years. However, the experiment was privately funded and the relevant cost data was not published, in addition to its research and use being limited to the authors. Hence for this analysis, the decision of cultivation methodology wan only limited to open ponds and PBRs.

section, further description will be afforded to production models that have attempted to include bio-fixation of carbon and nitrogen in its input set.

Carbon sequestration

The carbon bio-fixation benefit of microalgae is based on the photosynthetic process in microalgae growth that converts carbon dioxide to biomass (Chisti, 2007). The higher photosynthetic efficiency of microalgae compared to terrestrial plants has suggested it has greater carbon bio-fixation potential (Packer, 2009), especially using flue gas[20]. This was shown to occur relatively efficiently in smaller scaled/experimental settings with potential for larger scale production with a commercial use of the biomass (Sakai et al., 1995; Zeiler et al., 1995). Kadam (1997) demonstrated that through an auxiliary process (i.e. monoethanolamine or MEA process), the recovery and subsequent use of carbon dioxide from flue gas was financially viable (using proxy price of the resulting lipids). Wang et al. (2008) added that this would create a more efficient growth cycle in the carbon-rich environment and a cost-efficient input option. However, a review of algae species found that the optimal concentration of carbon dioxide and the bio-fixation capabilities was dependent on the specific species (Ono & Cuello, 2003), which would then affect the value of the resulting biomass. Pokoo-Aikins et al. (2010) published one of the most comprehensive scenario-based microalgae biodiesel TEA based on flue gas bio-fixation. Their results suggested that under optimal conditions and assumptions, biodiesel production from microalgae is competitive to other biomass-based oils from food crops but implied an inability to compete with fossil fuels. Rosenberg et al. (2011) suggested that although currently the financial feasibility of microalgae production is questionable, commercially valuable products from algae biomass could encourage the potential for an integrated facility allowing for bioremediation of carbon dioxide, which has been shown to occur at high rates.

[20] The gaseous output from power plants, rich in carbon dioxide, which is often released into the atmosphere.

Nitrogen sequestration

As with carbon sequestration, wastewater treatment of nitrogen and nitrates, a major cause of eutrophication (Pittman et al., 2011), had been discussed in the report by Benemann and Oswald (1996) as a key external benefit to microalgae production. The use of algae and microalgae in wastewater treatment had been widely employed, especially in the United States (Hoffmann, 1998) and more recently, Australia (Batten et al., 2013). A study on algae nitrogen bio-fixation properties with two sources of wastewater confirmed such positive findings on efficiency of treatment (Woertz et al., 2009) with other studies suggesting that a microalgae biofuel would only be potentially financially viable in scenarios that account for wastewater treatment (Lundquist et al., 2010; Pittman et al., 2011). This treatment of wastewater is also more efficient compared to other examples of constructed plant-based wastewater treatment systems (Idris, Jones, Salzman, Croatto, & Allinson, 2012). This was largely supported in a review and experimental of the potential of commercially viable output from bio-fixation of wastewater through microalgae (Christenson & Sims, 2011).

Early studies also suggest the potential for microalgae biomass use as nitrogen-rich fertiliser with nitrogen saturation (Benemann, 1979). However, studies have indicated an inverse relationship between nitrogen bio-fixation and lipid and carbohydrate production (Suali & Sarbatly, 2012), which is fundamental for the production of biodiesel (Lardon et al., 2009; Williams & Laurens, 2010) and ethanol (Amin, 2009; Harun, Danquah, & Forde, 2010) respectively. Conversely, the limiting of nitrogen then affects use of the biomass as valuable fertilisers since nitrogen is an essential element in this instance (Mata et al., 2010). This then creates a trade-off between the most efficient pathway to maximise the external and commercial benefits.

3.2.2.3. Output production stage: uses of biomass

There have been many uses of value for microalgae biomass that have driven research and attempts at commercial production (Alabi et al., 2009). However, in terms of production models, the commercial output product has generally been limited to a single product with some mention of the potential for commercial co-products or residual products to drive financial feasibility. This section outlines the potential high-value output products of microalgae biomass and suggests the technical feasibility of each of them in a multiple output process[21].

Biodiesel

Microalgae biodiesel is the main driver of production and feasibility research of microalgae in recent years. This is primarily due to the high lipid accumulation of the microalgae biomass on cultivation (S. A. Scott et al., 2010). Also, in the context of Australia, diesel consumption can be similar to petrol/gasoline, particularly in states (Western Australia and the Northern Territory) with large mining industries or significant off-road users (Ball et al., 2014). Microalgae biodiesel is produced from transesterification (a chemical conversion) of the lipids contained in the cells of the harvested biomass, which can be up to between 50% (Neenan, Feinberg, Hill, McIntosh, & Terry, 1986) and 70% (Amin, 2009) of the biomass cells. Research comparing microalgae biodiesel and regular (petroleum) diesel have largely favoured the notion that there is a high degree of technical substitution between the two, and if implemented, especially in blended fuels, it would require limited (Balat, 2010; Scragg, 2003) to no conversion of diesel engines (Xue, Grift, & Hansen, 2011). There are also supporting arguments for the superiority of microalgae to other biofuels as a technically and financially viable substitute (Chisti, 2008). Early research into the biodiesel production from

[21] There are other uses for microalgae such as in cosmetics and food pigments (Spolaore, Joannis-Cassan, Duran, & Isambert, 2006) that are not addressed in this study. The focus in this section and for the modelling in this study is on high-value commercial uses that have been among the most touted and relatively most well researched.

microalgae found that biodiesel production with wastewater and flue gas treatment was not commercially viable, let alone competitive with fossil fuels; requiring research and development of technology and algae phycology (Benemann et al., 1982; Benemann & Oswald, 1996; Neenan et al., 1986). It would be useful to note that in addition to advancements in the production of microalgae biodiesel, the price of fossil fuels in transport has also increased substantially since the time of this early research.

A number of studies in the last decade have focused on the specifics of the biodiesel production process that would make production technically and financially feasible. These have included research into specific algae species and the associated nutrient demands that would result in the most efficient outcome (Tsukahara & Sawayama, 2005), developments in cultivation methodologies for more productive outputs (Huntley & Redalje, 2007), life-cycle analyses of biodiesel production and/or combustion (P. K. Campbell et al., 2009; Darzins et al., 2010; Lardon et al., 2009; Sander & Murthy, 2010; Stephenson et al., 2010), and comparisons with similar diesel/biodiesels to justify commercial and policy support (Batan, Quinn, Willson, & Bradley, 2010; P. K. Campbell et al., 2011). These have given rise to numerous reviews of biodiesel production in the literature addressing aspects from cultivation to transesterification, and the developments made to the processing (Ahmad et al., 2011; Brennan & Owende, 2010; Dragone et al., 2010; Mata et al., 2010; Pienkos & Darzins, 2009; S. A. Scott et al., 2010; Shen, 2009; Williams & Laurens, 2010; Yeole, Aglave, & Lokhande, 2009)

The potential for microalgae biodiesel production has also inspired studies to use production pathways that assume the best-case scenarios. Given the infancy of the technology, these scenarios are often based more on experimental or hypothetical analyses. These have included studies looking at the best-case scenario for production of biodiesel (Brentner et al., 2011; Lundquist et al., 2010), biodiesel/algae oil production through carbon sequestration (Alabi et al., 2009; Pokoo-Aikins et al., 2010), and production pathways dependent on nitrogen saturation (Lardon et al., 2009). While these studies have added to finding more efficient pathways into microalgae biodiesel production, there has been little concrete evidence to suggest a competitive and feasible product relative to fossil fuels, despite the technical feasibility of the processes and biodiesel performance (Francisco, Neves, Jacob-Lopes, & Franco, 2010).

Biogas

Early attempts to convert solar energy to electrical power through microalgae biogas[22] were mostly hypothetical, experimental, and pilot-scaled. Oswald and Golueke (1960) presented one of the earliest studies into biogas conversion of microalgae biomass. As with biodiesel research at that time, technical feasibility was much touted, but the financial feasibility was less convincing. There are generally three pathways of production of biogas from microalgae[23]: (1) anaerobic digestion, (2) gasification, and (3) pyrolysis (Brennan & Owende, 2010; Tsukahara & Sawayama, 2005). Anaerobic digestion has been the relatively more common option in recent research (Collet et al., 2011; Harun et al., 2011; Vergara-Fernández, Vargas, Alarcón, & Velasco, 2008; Zamalloa et al., 2011).

Often the technical and financial research has suggested the importance and potential for biogas as a co-product to improve the feasibility of microalgae biomass and more importantly, biodiesel production. Biogas can be produced as a commercial co-product

[22] The biogas typically consists of 60% methane, and 40% carbon dioxide and other trace gases (Alabi et al., 2009).

[23] The three conversion processes are biochemical (anaerobic digestion) and thermochemical (pyrolysis and gasification) processes to convert the biomass into biogas. A brief description on each process can be found in a paper by Wang et al. (2008).

(Razon & Tan, 2011) or as an input for energy needs in the cultivation and processing of the biomass (P. K. Campbell et al., 2009; Collet et al., 2011). Harun et al. (2011) suggested that a biogas-biodiesel output from microalgae production yielded the highest energy output per weight of biomass. Conversely, Alabi et al. (2009) suggested that producing biogas as a co-product might not be technically feasible given the loss of carbon from other processes (e.g. lipid extraction). Nevertheless, biogas as a co-product is still potentially feasible, even with minimum carbon requirements, through allocative scenarios for the output products that can be recycled as production inputs. There is a research gap in that no study has attempted to evaluate biogas production in this manner.

Ethanol

Another class of biofuel that can be produced from microalgae biomass is a variant of bio-petrol (i.e. ethanol). Ethanol is typically produced from the fermentation of starch, which is also present in microalgae biomass (Amin, 2009) and is potentially more sustainable than ethanol from conventional feedstock (Pienkos & Darzins, 2009). Despite touting for the potential of microalgae biomass as an alternative bioethanol feedstock (Harun et al., 2010), a later article by Harun et al. (2011) suggested that this bioethanol yielded the lowest energy output from the algae biomass, but did indicate a higher energy output through co-product allocation. Alabi et al. (2009) disagree, asserting that ethanol as a primary output from algae biomass/cake has a higher energy output and also, higher GHG reductions than biogas. Some studies presented the production of bioethanol as the only output production of the cultivation, but based the main purpose of production on carbon sequestration (Hirano, Ueda, Hirayama, & Ogushi, 1997; Hirayama et al., 1998), and did not highlight the commercial value of the product.

In terms of ethanol as a co-product to biodiesel, few studies have attempted to evaluate this output pathway. Sander and Murthy (2010) allocated ethanol production from residual algae biomass in an LCA study to compensate carbon credits through maize feedstock replacement in the biodiesel production process, but not as a commercial output complimentary to biodiesel. Hence, there is a gap in the production literature for microalgae ethanol production at a more detailed extent (similar to that of the primary biodiesel output) in a multiple output analysis.

Stockfeed/animal and aquaculture nutrition

The composition of algae cells, even residual post-lipid extraction, has been suggested to support algae's use in stockfeed and aquaculture nutrition (Benemann, 2013). The high protein (15 to 71%) (Alabi et al., 2009), non-toxic nature (even grown in wastewater cultures) of the biomass has made it an experimentally sound choice for various poultry, cattle, and fish (de la Noue & de Pauw, 1988), and algae even provides benefits as a supplement for pet food (Spolaore et al., 2006). Currently, 30% of microalgae produced is used in animal and aquaculture feed (Becker, 2007). It is naturally a vital diet for aquaculture larvae of molluscs (in particular), shrimps, and certain fish species, in addition to live prey (Muller-Feuga, 2000; Spolaore et al., 2006). For example, in Australia, cultivated microalgae forms commercial feed for oysters, prawns, abalone, and zooplankton (M. R. Brown, Jeffrey, Volkman, & Dunstan, 1997). Also, the introduction of microalgae in rearing ponds facilitates environmental conditions in the medium (e.g. pH and oxygen levels) enabling better growth of the aquaculture (Chuntapa, Powtongsook, & Menasveta, 2003). Attempts at using other sources of nutrition for the abovementioned aquaculture have not proven as successful as live microalgae (Hemaiswarya, Raja, Ravi Kumar, Ganesan, & Anbazhagan, 2011).

The high costs and the infant state of mass production technology however, limit microalgae's application as a mass stockfeed for aquaculture (Benemann, 1992; Borowitzka, 1997; De Pauw, Morales, & Persoone, 1984; Hemaiswarya et al., 2011). While the technical feasibility of microalgae as terrestrial and marine feedstock has been much researched and touted, there has been no study into the economics of a mass cultivation for feed. There is a significant potential for residual or co-product biomass to be allocated for livestock and aquaculture industries, which spend about $2 billion on aquaculture and livestock imports to meet consumer demand, and can profit from a potential $7 billion export market (across both industries) (Cribb, 2013).

Human nutrition

The cultivation of microalgae for human nutrition represents the primary motivator for most current commercial production of microalgae. Historically starting in China (Spolaore et al., 2006), specific species of algae are cultivated in open-ponds, for nutritional purposes (Pulz & Gross, 2004). In particular, *Spirulina* has been found historically to provide certain populations with a substantial portion of nutrition, in particular protein and amino acids, more effectively than eggs, milk, and soybeans (Alabi et al., 2009; de la Noue & de Pauw, 1988; Kay & Barton, 1991), which has been substantiated in biochemical and nutritional analysis (Becker, 2007; M. R. Brown et al., 1997). However, the substantial costs of production have resulted in it being marketed as a premium health food (Becker, 2007). It is suggested that an increase in cultivation capacity and consumer acceptance could reduce the impact of potential food shortages in the future (Fujiwara-Arasaki, Mino, & Kuroda, 1984). However, there is currently no market for human nutrition products from a residual biomass, despite its high protein content (Alabi et al., 2009; Becker, 2007). Given that most production-economics studies for microalgae attempt to justify potential biofuels rather than current commercial products, there has not been a similar degree of study into microalgae production specifically for human nutrition, in addition to any analysis through co-production.

Fertilisers

Microalgae biomass can also be potentially used as fertilisers due to its nitrogen to phosphorus ratio (Benemann, 1979; Mata et al., 2010) and protein content, amongst other nutrients (Wilkie & Mulbry, 2002). This is particularly applicable to microalgae cultivated in nitrogen-rich wastewater, with findings of an efficient nutrient density relative to conventional agricultural fertilisers (de la Noue & de Pauw, 1988). Another pathway for microalgae biomass to become fertiliser is through bio-char. Bio-char is a residual output of pyrolysis processing of the biomass into bio-oil and biogas (Brennan & Owende, 2010). There have been successful studies in the technical feasibility use bio-char as fertiliser, with findings of efficient carbon sequestration resulting from their cultivation, processing, and use (Lal, 2008; Lehmann, Gaunt, & Rondon, 2006; Marris, 2006). Peralta, Sanchez, and Kafarov (2010) have suggested that producing bio-fertiliser from residual microalgae biomass increases the potential of biofuel production being financially feasible. However, there have been no quantitative production studies to date that present fertilisers as an output for production, either primary or complementary, despite research indicating their high potential.

3.2.3. Choice of cultivation location

Despite being a hypothetical production study, consideration was given to the production location. This was to attempt to ensure a more accurate estimation of the financial feasibility based on cost and production parameters, particularly the effects of climate on cultivation. Darzins et al. (2010) identified Karratha, Western Australia (WA), as an ideal location for analysis. Key reasons for basing the study in Karratha were the ideal conditions for large-scale microalgae cultivation and access to a waste CO_2 source (Darzins et al., 2010). This echoed findings from other research reports on Karratha having ideal conditions for cultivation such as climate and elevation (Borowitzka et al., 2012; L.E.K. Consulting, 2011). Outside of theoretical and hypothetical assessments, Karratha has been a choice for large-scale producers to cultivate microalgae. Initial investments by Aurora Algae[24] and Muradel[25] were made in the region but both have discontinued operations due to the high costs of production and more importantly, due to the uncompetitive nature of microalgae biofuels with fossil fuels to garner sufficient market return. More recently, Plankton Farms have begun operations in the region to produce high-value outputs, namely nutrition compounds. The company's representatives suggested that this output choice was the key reason why their operations would be financially feasible unlike their predecessors in microalgae production[26].

3.2.4. Approach to techno-economic analysis

This review of the production literature contributed to defining the scope for the techno-economic model used in this study. Firstly, it identified that although PBRs represent among the more technologically advanced systems and with higher biomass yields, the open-pond system is to be the more likely choice for a commercial or large-scale producer within the near future due to the lower capital and energy costs.

Secondly, the multi-output production system would require identifying the range of output products to be modelled. Biodiesel was selected as the primary biofuel output over ethanol given the research interest surrounding the efficient lipid accumulation (S. A. Scott et al., 2010) and higher energy content of biodiesel (Chisti, 2008). Also, as previously mentioned, there is a large market for this fuel in states (WA and NT) that have large mining industries. In terms of non-biofuel outputs, there would have to be enough product alternatives to ensure

[24] http://www.abc.net.au/news/2013-08-15/algae-farm/4889622
[25] http://www.abc.net.au/news/2013-05-20/nrn-algae-leaves-karratha/4699980
[26] http://www.abc.net.au/news/2015-12-14/plankton-farms-plans-for-karratha-algae-plant/7016678

sufficient variation in the sensitivity of the financial feasibility in terms of biomass allocation for outputs; there would be some limitations to fit with the premise of integrating the microalgae production system with existing complementary industries either in agriculture or aquaculture. Despite all of the outputs identified in this review being technically feasible in a multi-output production system, only three are chosen for the actual analysis. In addition to biodiesel, the alternative output products chosen are aquaculture feed and agricultural fertiliser. This was again to fit the premise of microalgae production being integrated with a complementary industry that could also provide a source of waste effluent i.e. high nutrient content wastewater. Although this limited the scope of the techno-economic model, it did address the broader research question surrounding integrated production systems.

The study employed by Darzins et al. (2010) was chosen as a reference from which to extend. This study had detailed the approach for TEA methodology in a microalgae production facility, particularly the relevant costs and production parameters for a Karratha-based production system. They also illustrated the production pathway from cultivation up to transesterification to biodiesel, which clearly identified key mass flows that would be important for this study.

3.3. Methodology

Similar to the reference paper by Darzins et al. (2010), this model was designed and scenarios simulated using Microsoft Excel.

3.3.1. Mass balance framework[27]

This techno-economic model used mass balance frameworks to account for the changes in mass based on parameters through the production system. The mass flows were mostly

[27] The figures in Appendix B illustrate the conceptual and final mass balance frameworks used in this study.

derived from the parameters outlined in this section, which was based on percentage changes in respective processes. Only the conversion of microalgae oil to biodiesel through transesterification was based on mass stoichiometry, which involved balancing chemical equations and using the molecular masses to determine the mass flows. The process was divided into two stages: (1) cultivation and harvesting, and (2) output production. As this study was a simulation of potential production, many process assumptions were required.

3.3.2. Cultivation and harvesting

The microalgae biomass would be cultivated in intensive open ponds. As previously mentioned, this method was chosen as the more likely choice over PBRs, which are significantly more costly for a hypothetical investor. An unnamed, hypothetical microalgae species was cultivated based on assumptions outlined in the literature regarding various parameters such as the growth rate, lipid accumulation, and nutrient requirements. Unlike the model presented by Darzins et al. (2010), this study made the assumption of a wastewater growth medium with a defined carbon, nitrogen, and phosphorus content (Metcalf, Eddy, Tchobanoglou, & Burton, 1991). These nutrients would then be supplemented by carbon dioxide assumed to be refined from flue gas, and urea and diammonium phosphate (DAP) as fertilisers based on nutrient availability from the wastewater medium for growth of the microalgae cells.

The parameters defining the hypothetical strain of microalgae are detailed in Table 3.1. These parameters would determine the nutrient requirements for growth from an initial microalgae ‘seed’ culture.

Table 3.1: Baseline microalgae strain parameters.

Parameter	Value	Units	Source
Algae content			
Protein content	7	%	Suali and Sarbatly (2012)
Lipid content	40	%	Darzins et al. (2010)
Extractable TAGs	95	%	Davis et al. (2014)
Carbohydrate content	50	%	Darzins et al. (2010)
Algae cell composition			
Carbon	0.538	%	Lardon et al. (2009)
Nitrogen	0.109	%	Lardon et al. (2009)
Phosphorus	0.024	%	Lardon et al. (2009)
Minerals, nucleic acids, nitrates, fibre	0.329	%	Rebolloso-Fuentes, Navarro-Pérez, García-Camacho, Ramos-Miras, and Guil-Guerrero (2001)
Molar mass of TAG	842		Ma (2012)
Molar mass of R	223		Ma (2012)

Further base assumptions pertaining to the cultivation of the microalgae biomass are outlined in Table 3.2. A base assumption of 10% was made for the proportion of effluent from the initial harvest that would be recycled for growth medium.

Table 3.2: Facility and cultivation baseline parameters.

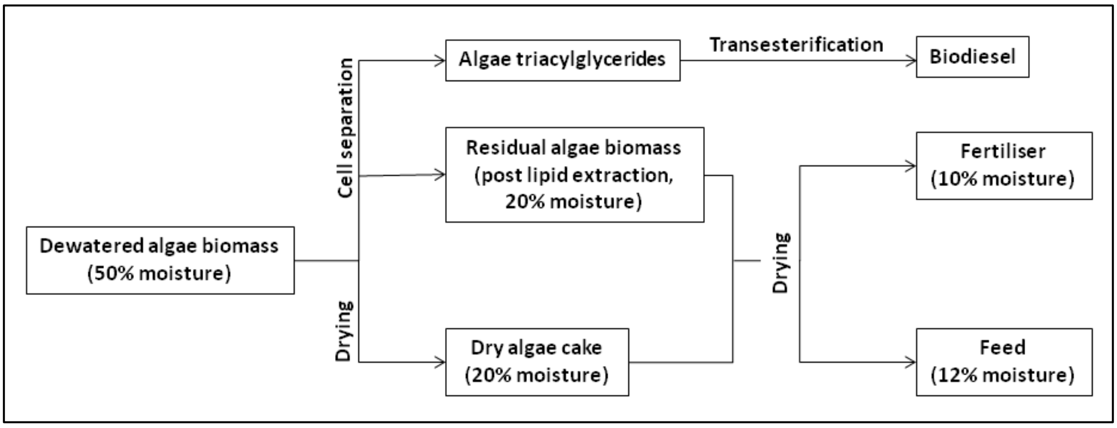
Parameters	Value	Units	Source
Total farm area	250	ha	
Area for ponds	175	ha	
Area for infrastructure	75	ha	
Number of ponds	10		
Total cultivation surface area	1,366,000	m^2	Darzins et al. (2010)
Total ponds volume	273,000	m^3	Darzins et al. (2010)
Days of operation	340	days/year	
Production rate	20	$g/m^2/day$	
Hours of production	12	hours	
Algae concentration in ponds	0.6	g/l	Darzins et al. (2010)
Algae concentration after cultivation	60	g/l	Darzins et al. (2010)
Proportion of effluent recycled after harvest	10	%	
Key fertiliser content			W. Curran (2015)
Urea nitrogen content	0.46	-	
DAP nitrogen content	0.18	-	
DAP phosphorus content	0.46	-	
Wastewater content per litre			Metcalf et al. (1991)
Water	999.3	g/l	
Carbon	80	mg/l	
Nitrogen	20	mg/l	
Phosphorus	4	mg/l	
Bio-mitigation efficiency			
Nitrogen	99	%	Woertz et al. (2009)
Phosphorus	99	%	Woertz et al. (2009)
Carbon	25	%	Zeng, Danquah, Chen, and Lu (2011)
Climate			
Location	Karratha/Port Hedland, WA		Darzins et al. (2010)
Net evaporation of pond volume per day (%/day)	4.11%		Bureau of Meteorology[a]

[a] Calculated as from monthly rainfall (Bureau of Meteorology, n.d.-b) and monthly evaporation statistics (Bureau of Meteorology, n.d.-a).

3.3.3. Output production

The resulting biomass was harvested through flocculation and centrifugal drying. This higher concentration algae 'slurry' was then proportioned into the three output products: biodiesel, agricultural fertiliser, and aquaculture feed. The mass balance flows from harvested biomass to the three final output products is shown in Figure 3.3.

Figure 3.3: Mass flows from cultivation output to final outputs.



3.3.3.1. Biodiesel from transesterification

The biodiesel output was assumed to be from a transesterification process, with the lipids extracted from the harvested microalgae biomass. The proportion of biomass intended for biodiesel production would first go through a cell separation stage to isolate the triacylglycerides (TAGs or lipids) from the biomass. These lipids would then be converted into liquid fatty acid methyl ester (FAME) fuels (with glycerol by-product) through an akali-catalyzed (with potassium hydroxide) transesterification with methanol. While much of the processes thus far were modelled based on proportion mass flows, this process used mass stoichiometry (Appendix A). The molar mass for the fatty acid component (R) is given in Table 3.1. An assumption of biodiesel recovery at 99.9% was used as per the protocol of West, Posarac, and Ellis (2008).

Methanol is typically added in excess (Darzins et al., 2010; Suali & Sarbatly, 2012), with this study using a 6:1 ratio of TAG. Excess methanol was recovered at a 96% efficiency (West et al., 2008) and recycled into the transesterification process. Lost and used methanol was then compensated for with additional methanol input to maintain the 6:1 ratio.

However, there was some loss in FAME production when the TAG reacted with the potassium hydroxide catalyst (saponification), forming a potassium soap and glycerol (Darzins et al., 2010). The glycerol in this stage was assumed to be unrecoverable. Excess potassium hydroxide catalyst that did not react with the TAG was then neutralised with phosphoric acid to produce tri-potassium phosphate salt and water.

3.3.3.2. Fertiliser and feed production

The fertiliser and feed in the model was assumed to be at higher concentrations of the harvested slurry, with the fertiliser at 10% moisture content and feed at 12%. An assumption was also made that any post-lipid extraction residue could be allocated for feed or fertiliser through the same drying process. Although the final nutritional content could be affected, the assumption was made that the final feed and/or fertilisers was produced from all sources of biomass (primary or residue).

3.3.4. Capital cost estimation

The capital cost estimation was primarily based on equipment listed in three studies, the seminal paper by Benemann and Oswald (1996), the reference paper by Darzins et al. (2010), and a recent study by Davis et al. (2014). Given the different plant capacities and periods of when these reference papers were published, the respective equipment costs were scaled according to both the size of the plant in this study and the year, which was factored to 2014 (Table 3.3). The scaling factors of the equipment according to plant capacity were based on the sixth-tenths factor rule (Peters, Timmerhaus, & West, 2003) and the capital costs were inflated based on the Chemical Engineering Plant Cost Index (CEPCI). As these indices would result in cost estimation in the USA, a location factor of 1.4[28] (Bent & Humphreys, 1996; Humphreys, 2005) was also used to adjust for the plant being located in Australia.

Table 3.3: Fixed capital based on 10-pond facility with baseline assumptions.

Fixed capital	Cost (US$)	Source
Microalgae growth		Benemann and Oswald (1996)
Pond construction	2,280,000	
Mixing paddle	1,900,000	
CO_2 Feed system	1,634,000	
Water & nutrient system	1,976,000	
Waste treatment (blow-down)	380,000	
Harvest and concentration		Benemann and Oswald (1996)
Settling Tanks/Flocculation	3,420,000	
Lipid extraction		Darzins et al. (2010)
Three phase centrifuge/Hot Oil	1,791,000	
Transesterification		Darzins et al. (2010)
Material Storage	13,898,000	
Processing equipment	28,728,000	
Utility equipment	5,349,000	
Biomass drying		Davis et al. (2014)
Dryer	1,087,000	
Storage		Davis et al. (2014)
Diesel storage	570,000	
Biomass silos (3 month storage)	1,395,000	
Total depreciable fixed capital	62,443,000	
Fixed capital investment (incl location factor)	326,105,000	
Total purchase cost of fixed capital	383,653,000	

[28] The location cost factor is a factor that encapsulates the total cost differences from one country to another. The elements captured in this factor are outlined in Bent and Humphreys (1996, p. 76).

In addition to the machinery costs, factors detailing the direct and indirect costs were employed based on a solid-fluid processing plant (Peters et al., 2003) (Table 3.4) to a total factor of 2.88 of the fixed capital investment.

Table 3.4: Ratio factors for estimating capital investment for solid-fluid processing plant.

Cost factor	Ratio
Indirect cost factors	
Engineering and supervision	0.32
Construction expenses	0.34
Legal expenses	0.04
Contractor's fees	0.19
Project contingency	0.37
Working capital (of FCI)	0.15
Direct cost factors	
Installation	0.39
Instrumentation and controls	0.26
Piping and insulation	0.31
Electrical facilities	0.10
Buildings	0.29
Yard improvements	0.12

Source: Peters et al. (2003, p. 251)

3.3.5. Operating cost estimation

Given that the hypothetical facility was located in the Karratha region of Western Australia, much of the operating costs (Table 3.5) are based on unit prices from providers closest to the region. For particular unit costs where location specific prices could not be easily obtained (particularly for non-commercial research), prices were derived from existing databases and recent studies. Labour costs were derived as an indicative figure based on personnel required as detailed by Davis et al. (2014), scaled by the output per day. The trade waste provider in WA only listed costs for disposal of nitrogen and phosphorus effluents and therefore, these were the only disposal costs for effluents in production. Annual maintenance (7% of fixed capital), supplies (15% of maintenance cost), and insurance (1% of fixed capital) costs were derived from ratios outlined in Peters et al. (2003). An assumption was made that pure carbon dioxide was obtained at no cost as waste from another industry (e.g. power generation); the no-cost assumption for carbon dioxide is not uncommon in techno-economics of microalgae (Zamalloa et al., 2011).

The energy requirements were derived based on a scaling of figures obtained in the literature and data on historical costs for the region (ACIL Tasman Pty. Ltd, 2013; Independent Market Operator, 2014). The electricity requirements for the entire operation (29,119.37 W per 100,000 kg/year) were derived from Jorquera et al. (2010) and scaled based on the mass of biomass produced. The energy requirement from natural gas for biomass drying (3,556kJ/kg of water removed) was obtained from Sander and Murthy (2010).

Table 3.5: Annual operating costs.

Operating cost	Cost	Unit	Source
Nutrients/fertilisers			
Urea	750.00	US$/t	The World Bank
DAP	550.89	US$/t	The World Bank
Chemicals (concentration)			
Hexane (100%)	1178.01	US$/t	Davis et al. (2014)
Methanol (100%)	590.00	US$/t	Methanex
Potassium hydroxide (50%)*	452.57	US$/t	†
Phosphoric acid (60%)*	497.83	US$/t	†
Sulphuric acid (60%)*	316.80	US$/t	†
Utilities			
Electricity*	0.46	US$/kW	Independent Market Operator (2014)
Water*	3.10	US$/t	Water Corporation (2014b)
Natural gas*	7.23	US$/GJ	ACIL Tasman Pty. Ltd (2013)
Effluent disposal			Water Corporation (2014a)
Annual permit charge*	199.45	US$	
Annual metering and sampling*	286.11	US$	
Nitrogen*	1.13	US$/kg	
Phosphorus*	0.33	US$/kg	

* Values obtained in AUD$ were converted to US$ using a representative exchange rate at 2014 of AUD$1=US$0.905149.

† Prices obtained from G Parry (personal communication, February 20, 2015) from Orica Chemicals Australia.

3.3.6. Output allocation and cost estimation

The baseline output allocation of the microalgae biomass was set at 40% for biodiesel and 30% each for fertiliser and feed. In addition, when biodiesel was produced, the post-lipid extraction residue was also allocated to producing an equal ratio of fertiliser and feed. Glycerol was produced as a commercial by-product with biodiesel. The prices for glycerol, fertiliser, and feed were obtained from Soley Biotechnology Institute's website, who published its estimated prices for respective microalgae products. The price for feed was based on shrimp feed prices given the potential for an industrial partnership with aquaculture farming. The price for biodiesel is based on the average retail diesel prices across the calendar (2014) and financial years (2014-2015) in WA rounded to the nearest 10 cents (Table 3.6). This was based on the assumption that the biodiesel produced is a direct substitute for commercial diesel i.e. a drop-in fuel.

Table 3.6: Output allocation and prices.

Output	Output allocation		Price	Unit	Source
	Primary	Residue			
Biodiesel	0.4		1.50	AUD$/l	Australia Institute of Petroleum[b]
Glycerol[a]			1.52	US$/l	Soley Biotechnology Institute[c]
Fertiliser	0.3	0.5	12.00	US$/kg	Soley Biotechnology Institute[d]
Feed	0.3	0.5	12.00	US$/kg	Soley Biotechnology Institute[e]

[a] Glycerol included as by-product when biodiesel is produced.
[b] http://www.aip.com.au/pricing/retail/diesel/index.htm
[c] http://www.soleybio.com/products/gylcerin.html
[d] http://www.soleybio.com/products/organic-fertilizer.html
[e] http://www.soleybio.com/products/fresh-microalgae.html

While some TEAs seek to determine a unit price for the respective output (Davis et al., 2011), which could be sold to wholesalers, distributors, or retailers, this study follows (Darzins et al., 2010) who attach a price to the output as representative of the likely price obtained from buyers. An assumption was made that the commercial prices listed on Table 3.6 would be obtainable by the producer when all four outputs were sold regardless to wholesalers, distributors, retailers, or consumers. This simplifies the revenue estimation process as it excludes the detailed supply chain (e.g. storage and transportation of outputs) and retailing (e.g. additional tanks and pumps) costs, particularly from the largely remote region of Karratha to consumers. The inclusion of specific supply chain and retailing costs would yield a more accurate estimate of revenue. However, the assumption made in this part of the analysis would not significantly affect the objective of determining the impacts of multiple outputs and benefits of industrial integration on financial feasibility.

3.3.7. Net present value, internal rate of return, and payback period

Net present value (NPV) analysis was conducted using the mass flows from the mass balance model outlined in the previous section. A common tool in forecasting process economics, NPV estimates the present value of future earnings by applying a discount rate to indicate the time value of the earnings with a given risk preference as shown in the equation below. CF_t is the cashflow at time t, r is the discount rate, and N is the years in which the NPV is calculated.

$$NPV = \sum_{t=0}^{N} \frac{CF_t}{(1+r)^t} \tag{3.1}$$

The future earnings took into account all revenue streams from the multiple outputs/co-products less capital and annual operating costs, depreciation, and tax. The financial valuation parameters are outlined in Table 3.7. These parameters also allowed the estimation of an internal rate of return (IRR), a discount rate that returned a zero NPV. Finally, a payback period was also calculated, which illustrated the number of years for the initial investment to be repaid without accounting for the time value of earnings.

The nominal discount rate was set at 10% as a simplified reflection of risk preference. This rate is lower than the 15% used by Darzins et al. (2010). However, Short et al. (as cited in Davis et al., 2014, pp. 56-57) suggested that in the absence of comparable discount rates in a related industry, a 10% is recommended. A straight-line depreciation rate of 4% of capital expenditure was applied based on the standard rate from the Australian Taxation Office (ATO)[29]. The base operation period was set at 20 years with production active for 340 days a year (Table 3.2). The tax rate of 30% was derived from company tax rates from the ATO. An inflation rate of 2% was used, similar to Darzins et al. (2010).

Table 3.7: Financial valuation parameters.

Parameter	Value
Discount rate	10%
Depreciation	4%
Operation period	20 years
Tax rate	30%

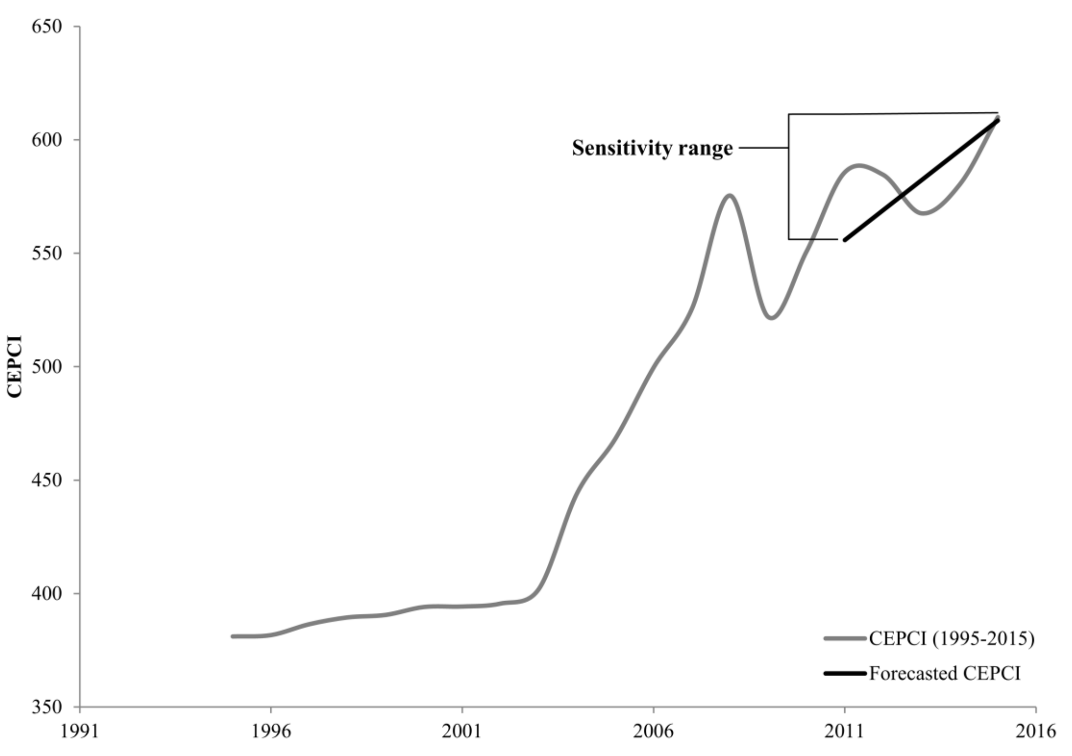
3.3.8. Sensitivity analysis

Sensitivity analyses in TEA test the impacts of changes in key parameters on the financial feasibility of the project (expressed in terms of NPV) (Borowitzka, 2013). A sensitivity analysis was conducted across a number of parameters from the baseline (Table 3.8). For this study, the sensitivity analysis would illustrate changes in the NPV based on changes in these individual parameters (Iloiu & Csiminga, 2009). It was conducted by varying a single parameter at a time. Although relatively simple, this method would provide important information on where the greatest impact to NPV lies (Borowitzka, 2013), similar to previous studies (Davis et al., 2011; Norsker et al., 2011; Stephens et al., 2010). These parameters were selected based on the availability of information about potential ranges and to have the highest potential impact on the valuation of the production system.

[29] https://www.ato.gov.au/business/depreciation-and-capital-expenses-and-allowances/capital-works-deductions/

Ranges for the growth rate and lipid content of microalgae were based on current and potential levels found in the literature (Darzins et al., 2010; Davis et al., 2011). The CEPCI range, used as a measure of capital cost inflation/variability, was defined as the maximum and minimum range between the years 2011 to 2015 and forecasted estimates from 1995 to 2010 by using Microsoft Excel's FORECAST function based on linear regression (Figure 3.4). This approach was used to incorporate a greater range of realistic variability to the CEPCI sensitivity range.

Figure 3.4: Sensitivity range for CEPCI.



The maximum discount rate (15%) was based on the higher rate used by Darzins et al. (2010) and the minimum (5%) was taken from Gómez, Rodrigues, Montañés, Dopazo, and Fueyo (2011); the latter used a low discount rate in an economic analysis of first-generation biofuels. The prices of feed and fertiliser were obtained from a range of respective products sold by the Soley Biotechnology Institute. The price ranges for DAP and urea were based on the minimum to maximum range for monthly estimates from 2010 to 2014 from The World Bank Global Economic Monitor (GEM) for Commodities. The lower bound for the diesel price range is based on the historical prices for diesel in WA rounded to the nearest 10 cents and the upper bound is chosen as a linear regression forecast of historical prices from 2007 to 2014 up to 2037 (30 years from the starting year), rounded to the nearest 10 cents. The electricity price and natural gas price ranges were obtained from historical prices obtained from the respective sources (ACIL Tasman Pty. Ltd; Independent Market Operator). The water price range was based on the 15 price steps for water provision in regional WA.

Table 3.8: Sensitivity analysis parameters and ranges.

Parameters (units)	Baseline	Range
Growth rate (g/m^2/day)	20	10 - 60
Lipid content (%)	40	10 - 60
Residue use (%)	100	0 - 100
Effluent recycle (%)	10	0 - 100
Operation period (years)	20	10 - 50
Proportion for biodiesel (%)	40	25 - 60
Residue for fertiliser (%)	50	0 - 100
CEPCI	580.2	555.79 - 609.99
Discount rate (%)	10	5 – 15
Price of biodiesel (AUD$/l)	1.50	1.30 - 2.30
Price of feed (US$/kg)	12	2.50 - 18
Price of fertiliser (US$/kg)	12	9 - 24
Urea price (US$/t)	750.00	121.46 - 870.49
DAP price (US$/t)	550.89	227.39 - 1409.90
Electricity price (AUD$/kW)	0.51	0.34 - 0.57
Natural gas price (AUD$/GJ)	7.99	5.02 - 11.56
Water price (AUD$/t)	3.43	2.06 - 6.78

3.3.9. Switch value analysis

Sensitivity analysis often draws on assumptions of likely changes in the parameters based on past events or interpretations of future outcomes. This may raise some ambiguity in the analysis. Switch values are point estimates for key parameters that result in the change in NPV to zero (Iloiu & Csiminga, 2009), thereby reducing the ambiguity of traditional sensitivity analysis. In the switch value analysis, the same parameters and discount rate utilised in the sensitivity analysis were used to derive switch values, and were compared with the ranges used in the sensitivity analysis. This showed the feasibility of the switch values based on the realistic boundaries of the sensitivity analysis. This was estimated using equation 3.2 where NPV_b and X_b is the baseline NPV and parameter respectively and NPV_1 and X_1 is the NPV and parameter in a chosen sensitivity boundary (Iloiu & Csiminga, 2009).

$$SV = \frac{(100 \times NPV_b)}{(NPV_b - NPV_1)} \times \frac{(X_b - X_1)}{X_b} \tag{3.2}$$

3.4. Results

In this section, the results from the analyses undertaken are presented. The first subsection outlines the baseline results from the financial valuation of the techno-economic model, based on parameters outlined previously. Subsequently, the results from the sensitivity and switch value analyses are outlined. The results from this study help to illustrate the potential financial feasibility of a multi-output production system and where opportunities to improve feasibility lie which leads into the discussion in the following section.

3.4.1. Baseline financial valuation

The results from the baseline financial valuation are shown in Table 3.9. The valuation found the NPV for the baseline to be just over US$ 5 million (2014 dollars) with an IRR similar to the discount rate of 10%. It was also estimated that for the capital investments, annual operating costs, and revenues across a 20-year period, the initial investment would take just over 20 years to repay.

The results showed that indirect and installation costs were a major proportion of capital expenditure, over that of purchasing actual equipment (Figure 3.5). This was often the case in financial valuation studies like the reference papers for this study (Darzins et al., 2010; Davis et al., 2014). Outside of these, the cost of the biodiesel production equipment (including cell separation and transesterification processes) was the highest proportion of capital expenditure. In terms of the annual operating costs, growth nutrients represented the main costs outside of annual maintenance and administrative costs (Figure 3.6), despite use of a nutrient-rich wastewater growth medium.

Table 3.9: Baseline financial analysis.

Capital costs	**US$**
Pond construction	8,170,000
Harvesting/concentration	3,420,000
Biodiesel production equipment	47,975,000
Biomass dryer	1,087,000
Storage	1,965,000
Recyclable inputs	26,000
Indirect costs	78,679,000
Installation costs	91,792,000
Working capital	57,548,000
Total capital outlay	*383,650,000*
Operating costs	**US$/year**
Growth nutrients	1,768,000
Flocculant	298,000
Processing chemicals	173,000
Utilities	431,000
Natural gas for dryer	262,000
Disposal costs	10,301
Tradewaste license/metering	486
Labour	26,760
Others (maintenance, supplies, insurance)	29,512,000
Annual operating costs	32,481,000
Total PV of operating costs (US$)	*276,528,000*
Revenue	**US$/year**
Biodiesel	2,191,000
Glycerol	0.29
Fertiliser	47,260,000
Feed	47,260,000
Total annual revenue	*96,712,000*
Total PV of revenues (US$)	*823,365,000*
Total PV of tax payable (US$)	*-157,672,000*
NPV (US$)	**5,011,000**
IRR (%)	**10%**
Payback period (years)	**20.2**

Figure 3.5: Capital cost allocation.

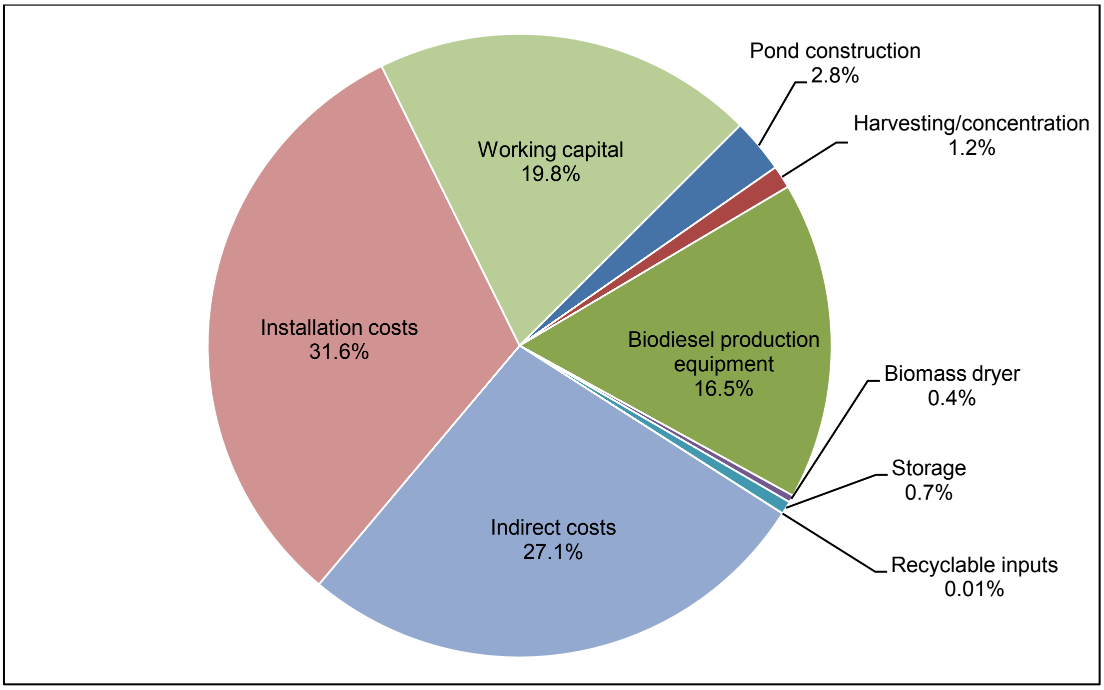
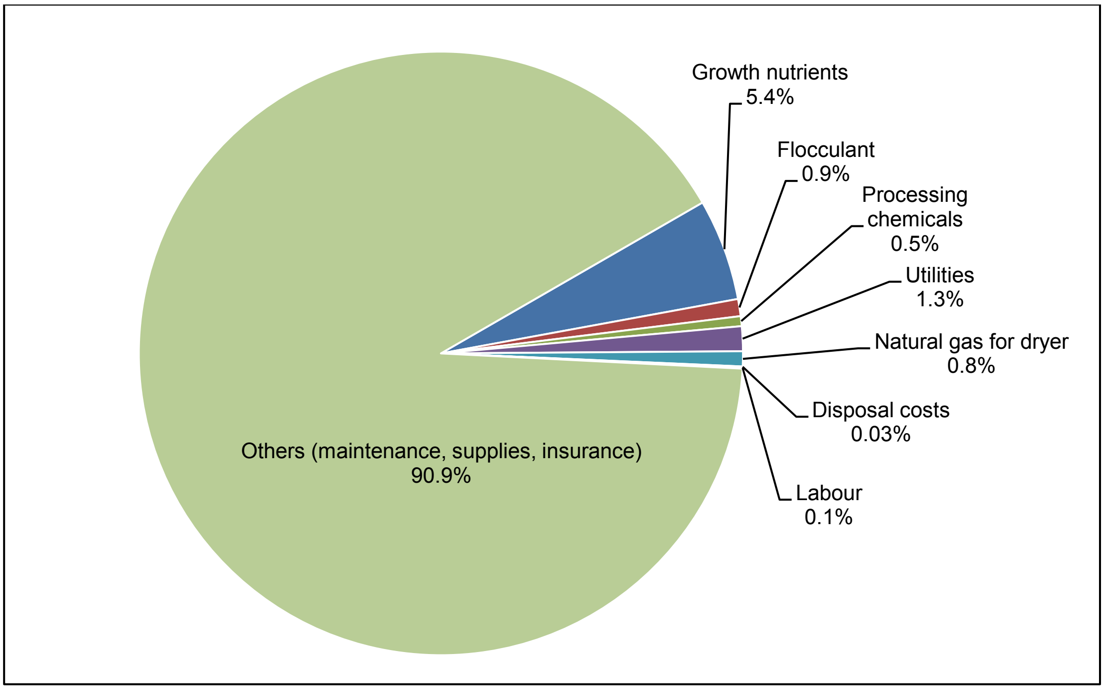


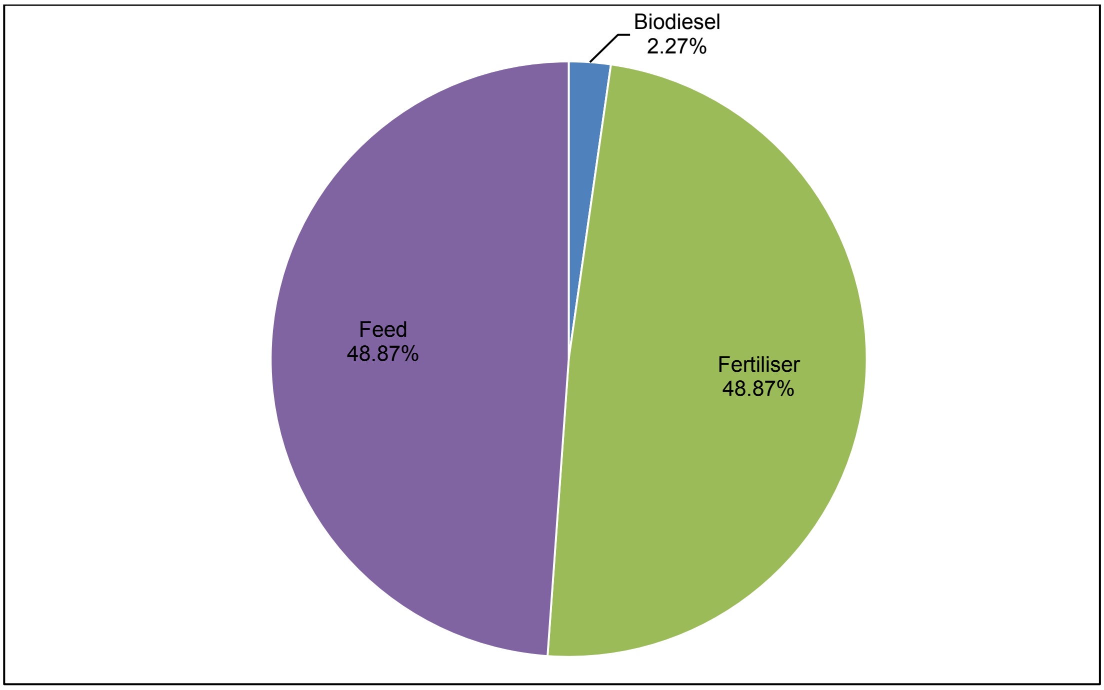
Figure 3.6: Annual operating cost allocation.



Note: Tradewaste, licensing, and metering charges excluded as relative costs were negligible (0.00% to 2 decimal places).

In terms of revenues, biodiesel contributed just over 2% of the revenues despite 40% of the biomass being allocated to biodiesel production as a primary use (Figure 3.7). This was due to the relative lower value of the biodiesel, which used diesel pump prices as a proxy assuming perfect substitution. Given the high-value nature of the feed and fertiliser products, these would likely represent the greater sources of revenue for the production system, even in alternative biomass allocation proportions.

Figure 3.7: Revenue allocation.



Note: Revenue from glycerol excluded as relative revenue was negligible (0.00% to 2 decimal places).

3.4.2. Sensitivity analysis

The sensitivity of the parameters outlined in Table 3.8 to the NPV of the facility operation is presented in Figure 3.8. The plot in (a) shows that potential increases in the growth rate of the algae strain can have the largest impact on the resulting NPV, particularly due to the increase in mass for feed and fertiliser sales. The sensitivity analysis also found that increasing emphasis on biodiesel production and strain engineering for higher lipid yields decreases the potential NPV, the latter due to the costs involved with having to extract the lipids from the biomass for biodiesel. Use of post-lipid extraction residue was found to be essential to the financial feasibility of the facility. Additionally, the price ranges for various inputs and utilities were found not to result in a negative NPV. A lower biodiesel price was also found to be offset by sales of feed and fertiliser and hence, not affect the feasibility based on the realistic range of potential prices for commercial diesel fuel.

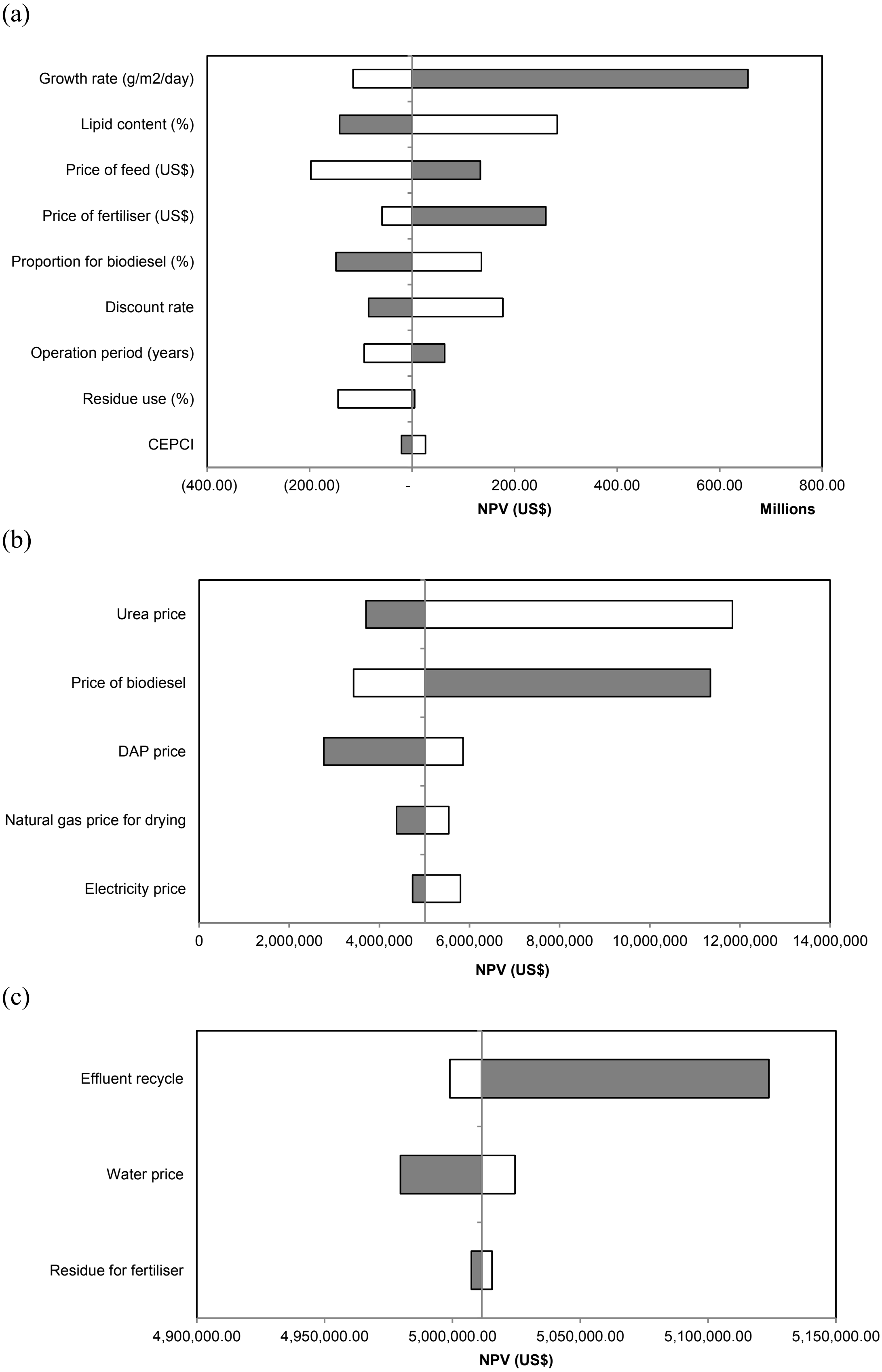
3.4.1. Switch value analysis

Only 6 out of the 14 parameters investigated had switch values that fell within the range of the sensitivity analysis boundaries (Table 3.10). The estimates suggest that much of the baseline parameters were operating around the switch value range, particularly the proportion of biomass allocated for biodiesel production. The estimate for residue use (96.65%) indicated that use of post-lipid extraction biomass to produce other (high-value) products is essential in ensuring the financial feasibility of the production system.

Table 3.10: Switch values.

Parameter	Direction	SV
Growth rate ($g/m^2/day$)	<	19.58
Lipid content (%)	>	40.54
Price of feed (US$/t)	<	11.77
Price of fertiliser (US$/t)	<	11.77
Proportion for biodiesel (%)	>	40.58
Operation period (years)	<	19.49
Residue use (%)	<	96.65
CEPCI	>	585.98

Figure 3.8: Sensitivity analysis plots.



Note: Grey bars represent increases and white bars represent decreases in parameter from baseline (see Table 3.8).

3.5. Discussion

3.5.1. Findings and contributions from analysis

As previously mentioned, the use of TEA in modelling the transesterification of microalgae lipids to biodiesel is not novel. However, with much of the qualitative literature suggesting the opportunities of feasible production, this study attempted to address two of the highlighted suggestions; these were the production of microalgae biodiesel in a multi-output framework and production in an integrated system with complementary industries. Additionally, the use of sensitivity and switch value analysis presented provided further information on the potential of microalgae biodiesel production in the abovementioned systems.

In order to maintain high growth rates of the biomass, fertiliser costs were a significant input factor in the financial feasibility. The use of wastewater was able to reduce these high growth nutrient costs. Utilising higher nutrient-containing mediums could potentially further reduce operating costs while also being an option for bioremediation of wastewater, either from municipal, industrial, agricultural, or aquaculture sources (Pittman et al., 2011), and improving sustainability of the biofuel production (Borowitzka, 2013).

This study also found that producing high-value co-products was essential for microalgae biodiesel feasibility, assuming perfect substitution of microalgae biodiesel with commercial fossil-based diesel. The revenue from these co-products offsets the high capital costs of the lipid extraction and transesterification equipment, and the comparably lower return from biodiesel. However, this suggested an opportunity cost for producers of microalgae products; a higher proportion of biomass devoted to biodiesel negatively affected the NPV of the system. This finding affirmed the direction of most commercial microalgae producers to focus on alternative high-value output products.

The analysis presented in this chapter represents a source of new information to the breadth of literature on techno-economics and microalgae biodiesel production. More importantly, it potentially contributed a new direction of techno-economics particularly for microalgae and other systems with multiple outputs. Often with infant technologies, financial feasibility is difficult to achieve at the start. Accounting for multiple outputs, particularly those with high values can suggest production pathways that improve financial feasibility and potentially attract investment. In addition, integrated production utilising waste streams from complementary industries could represent a major factor that would encourage both private and policy interest, especially when considering the economic benefits to various stakeholders.

3.5.2. Implications for microalgae biofuel industry development

If the production system is purposed for producing biodiesel rather than ensuring the highest NPV, a number of factors should be considered to ensure the feasibility (at least a positive NPV) of the system. Firstly, feasibility of microalgae biodiesel production to meet larger demands is dependent on improvements in the cost efficiency of biodiesel production equipment. The current efficiency of converting the biomass to usable biodiesel is insufficiently developed to allocate a greater proportion of biomass. Hence, while strain engineering to improve growth and lipid accumulation rates can improve the cost-efficiency of the cultivation system, feasibility of biodiesel production would benefit more from emphasis in improving this aspect of the production process.

Secondly, feasibility of microalgae biodiesel production could be improved through mutually beneficial production with complementary industries. The use of waste carbon dioxide (Brennan & Owende, 2010; Kadam, 2002; Khan, Rashmi, Hussain, Prasad, & Banerjee, 2009; Wang et al., 2008) and more relevant to this study, nutrient-rich wastewater, has been well documented in the literature (Batten et al., 2013; Mata et al., 2010; Pittman et al., 2011; Woertz et al., 2009). However, this study found that rather than just using the waste effluents in the cultivation of the biomass, there is the potential to also produce output products that can benefit the partnering industry. An example would be a production system integrated with aquaculture farming; the latter could provide a source of nutrient-rich growth medium while the microalgae system could provide feed, a significant input cost for aquaculture, through residue or co-product allocation of the biomass. Such integrated production systems could utilise potential synergy between the producers and industries.

3.5.3. Limitations and further research

The limitations to this study can be generally classified into two categories: (1) from the engineering perspective and (2) from the economic perspective. For the former, it can be suggested that the accuracy of both technical and financial aspects of this model could be refined. Use of process modelling software such as ASPEN HYSYS (Aspentech, 2012) or SuperPro Designer (Intelligen Inc) could be employed in future extensions to improve accuracy of mass and energy flows. Also, more detailed supply chain and retailing costs could be incorporated in future TEAs to yield more accurate financial estimates, particularly as the production technology improves and supply chain issues become a greater indicator of feasibility.

In addition, this study limited output products to biodiesel (from transesterification), fertiliser, and feed. The literature has identified that other products and processes can be utilised, which could introduce new output options (both energy and non-energy based) or more efficient processes (Borowitzka, 2013). The alternative energy products could include hydrothermal liquefaction (HTL) of the biomass into biocrude (Elliott et al., 2013), fermentation of sugars into ethanol (Alabi et al., 2009; Amin, 2009; Harun et al., 2010; Hirano et al., 1997; Hirayama et al., 1998), anaerobic digestion of the biomass into biogas/methane (Collet et al., 2011; Harun et al., 2011; Vergara-Fernández et al., 2008; Zamalloa et al., 2011); highly valuable human nutrition supplements could also be included as a non-energy output (Becker, 2007; Fujiwara-Arasaki et al., 1984; Spolaore et al., 2006). Hence, future iterations of the model could incorporate these alternatives to account for technological developments and policy/industry investment opportunities.

The modelling of the integrated production system was a major contribution to the research in this field. However, there is the opportunity to further detail some aspects of the impacts of the integration. In particular, the interaction between the microalgae production and complementary industry could be modelled to capture the benefits from the integration. This could include more accurate modelling of the waste effluent nutrient content, microalgae feed/fertiliser nutrient content and its impacts to (aquaculture) production, and the overall financial feasibility and economic benefits. Such analysis would give a better indication of the financial and economic value of integration of microalgae production with other industries.

Lastly, a number of both technical and financial parameters were derived from previous studies. While care was given to ensure the most recent assumptions and parameters can be used, the model would improve in accuracy from use of more precise production and financial data. These could either be obtained from concurrent small-scale experiments, agreements with biomass producers, and commercial producers of inputs and outputs. All three sources were considered during this study but resource limitations (time, monetary, and industrial linkages) had resulted in the use of values suggested in the literature.

From the economics' perspective, the financial valuation undertaken in this study could be extended for further analysis. Firstly, the use of sensitivity analysis helped to illustrate fluctuation in price and production but can be regarded as relatively simple (Borowitzka, 2013). Incorporating risk (Richardson, 2010) and policy elements into the modelling would provide further information on this topic. In particular, use of simulations that allow for variability across more than one parameter would contribute further to the economic aspects of this type of modelling. One such example has been attempted at part of this PhD and is presented in the following chapter.

3.6. Conclusion

The aim of this study was to assess the financial feasibility of microalgae biodiesel production in a multi-output framework, integrated with complementary industries.

The results suggest potential for the feasibility of the production through the integration with aquaculture industries. This is due to the benefits from bio-fixation of nutrient rich wastewater, and the opportunity of access to valuable feed and fertiliser inputs from the aquaculture industry's perspective. The microalgae production would benefit significantly from reduced input costs. A major hurdle identified was the large capital costs of microalgae production and processing. Hence, more high-value output products have often been preferred, stagnating the progress of biodiesel production. This study identified that simultaneous production of biodiesel with high-value co-products improves the financial feasibility of a microalgae biodiesel production facility.

These findings could prove consequential when considering the potential of increased biofuel use in the transport fuel market, both domestically and globally. Therefore, with the eventual winding down of mining and fossil fuel industries coupled with favourable cultivation conditions in Australia, this presents a potential opportunity for the development of a new sustainable industrial network that incorporates third-generation liquid biofuels.

Chapter 4. Techno-economic profit function

4.1. Introduction

Techno-economic analyses of microalgae biofuel production are useful to gauge the technical and financial potential of the related processes and direct research and development activities (Borowitzka, 2013). The lack of large-scale production facilities raises the importance of such hypothetical production studies at this infant stage of the technologies. These studies are often limited to the engineering discipline with aims centred on testing the feasibility of new technologies and increasing scales of production systems. The complexity of the interactions generally results in the analysis limited to consideration of profitability under a limited number of scenarios (e.g. Marchetti, Miguel, & Errazu, 2008), sensitivity of costs to different production assumptions (e.g. Davis et al., 2011), or minimum viable scale given the high capital cost involved in their establishment (e.g. Apostolakou, Kookos, Marazioti, & Angelopoulos, 2009).

Most previous study of the impacts of changes in prices of inputs and outputs on profitability were limited to sensitivity analyses (Davis et al., 2011; Norsker et al., 2011; Stephens et al., 2010). A major weakness of typical sensitivity analyses is that they often involve varying one parameter at a time (Borowitzka, 2013). While such simplistic analysis can help to identify where greatest impacts to feasibility can be experienced, it does not capture the full relationship between input and output prices, and profits for a producer in a system of prices fluctuating simultaneously. Furthermore, these studies do not measure the price elasticity of input demand and output supply from microalgae production, useful information when considering the impacts of changes in input and output prices. Also, with the potential of a multi-output production system, there has not been any analysis of the degree of substitutability between different outputs with changes in prices.

Most previous studies also consider production of only a single output, namely the biofuel. Davis et al. (2011) also suggested that algae biofuel economics might be further improved through development of a multi-output production system, with the spent algae biomass used for more valuable co-products beyond biogas for power generation. However, the potential benefits of multi-output production system, and the degree of substitutability between different outputs with changes in prices have not been previously explored.

These gaps in the literature can largely be attributed to the lack of commercial production of microalgae biofuels and the associated lack of available data for analysis. However, this notwithstanding, they also fail to take advantage of economic methodologies, which can shed greater insights into the production processes that they are simulating. In particular, the economic estimation of a restricted profit function (Lau, 1976) using simulation output can provide greater information on how profitability varies with input and output prices, but also how output supply and input use are also likely to change. Such profit functions are commonly produced in other industries like agriculture (Weaver, 1983), and fisheries and aquaculture (Andersen, Roll, & Tveterås, 2008; Asche, Gordon, & Jensen, 2007; Pascoe et al., 2011; Squires, 1987) and help to illustrate how producers might maximise profits with given prices by deriving price elasticities of input demand and output supply.

The main aim of this study was to determine how a potential microalgae producer of a multi-output system could maximize profits, accounting for variations in input and output prices. The techno-economic model from the previous chapter produced simulation-based production data that can be used to conduct such analyses. The available information on the fluctuations of input and output prices were used to simulate a range of production scenarios under different price conditions. The analysis identified how the output mix could be altered with changes to prices of diesel, feed, and fertiliser; and how fluctuations in input prices could influence the output mix. The aim was accomplished by deriving a restricted profit function for multi-product firms (Lau, 1976; Squires, 1987) using data obtained from Monte-Carlo simulations of the techno-economic model and estimating the related price elasticities of input demand and output supply.

The next section will discuss the methodology of the study, with reference to the relevant economic literature. Subsequently, descriptions of the data obtained from simulations, together with the results, will be presented. Finally, a discussion of the results and related implications will conclude the chapter.

4.2. Methodology

This study involved the econometric estimation of a restricted profit function using the simulated production data from the techno-economic analysis (TEA) from the previous chapter. As the system involved production of multiple outputs, the methodology involved was drawn from Lau (1976). Squires (1987) undertook a similar study involving multiproduct firms in a trawl fishery, and his notation is replicated in the following description.

The restricted profit function is defined as $HR(p; z)$ where HR is the restricted profit (total revenue less total variable costs), p is a vector of input and output prices, and z is a vector of quasi-fixed input factors. By Hotelling's (1932) lemma,

$$\frac{\partial HR(p;z)}{\partial p} = Y(p;z) \tag{4.1}$$

and

$$\frac{\partial HR(p;z)}{\partial z} = -p_z^* \tag{4.2}$$

where $Y(p,z)$ is a vector of positive outputs and negative variable inputs that outline the output-supply and input-demand functions for a level of quasi-fixed factors, and p_z^* is the shadow prices for the quasi-fixed factors (Lau, 1976). If the producer optimizes the level of quasi-fixed factors, the shadow price will be equal to the market price (Samuelson, 1953; Squires, 1987) such that p_z^* will be equal to p_z and,

$$\frac{\partial HR(p;z)}{\partial z} = -p_z \tag{4.3}$$

The optimal level of inputs and outputs given prices p and p_z is then given by

$$\frac{\partial HR[p,z^*(p,p_z)]}{\partial p} \tag{4.4}$$

where $z^*(p,p_z)$ is the long-run equilibrium of quasi-fixed factors given the range of prices (Pascoe et al., 2011).

In this study, the widely used translog functional form (Caves, Christensen, & Tretheway, 1980; Ray, 1982; Sidhu & Baanante, 1981; Weaver, 1983) was employed. The generalised translog function for a multiproduct function is given as (Burgess, 1974; Caves et al., 1980; Pascoe et al., 2011):

$$\begin{aligned} lnHR = \alpha_0 + \sum_i \alpha_i \, lnP_i + \frac{1}{2} \sum_{i \neq j} \sum_{j \neq i} \alpha_{ij} \, lnP_i \, lnP_j + \sum_i \alpha_{ii} \, ln^2 P_i + \sum_k \beta_k \, lnZ_k \\ + \sum_{k \neq l} \sum_{l \neq k} \beta_{kl} \, lnZ_k lnZ_l + \sum_k \beta_{kk} \, ln^2 Z_k + \sum_i \sum_k \beta_{ik} \, lnP_i \, lnZ_k \end{aligned} \tag{4.5}$$

where the observed short-run profit HR is a function of the prices of variable inputs (P_i) and outputs (P_j), and the quantities of respective quasi-fixed inputs Z_k and Z_l.

Theoretical consistency requires the profit function to be linearly homogeneous of degree 1, which is realised through imposing homogeneity conditions on input and output prices: (i) $\Sigma_i \alpha_i=1$, (ii) $\Sigma_i \alpha_{ij}=1$, and (iii) $\Sigma_i \beta_{ik}=0$. In practice, this is achieved by normalising the profit function by one of the outputs, in this case the feed output (P_f), resulting in the functional form,

$$\begin{aligned} ln(HR/P_f) = {} & \alpha_0 + \sum_{i>f} \alpha_i \, ln(P_i/P_f) + \frac{1}{2} \sum_{i \neq j \neq f} \sum_{j \neq i \neq f} \alpha_{ij} \, ln(P_i/P_f) ln(P_j/P_f) \\ & + \sum_{i>f} \alpha_{ii} \, ln^2(P_i/P_f) + \sum_k \beta_k \, lnZ_k + \sum_{k \neq l} \sum_{l \neq k} \beta_{kl} \, lnZ_k lnZ_l \\ & + \sum_k \beta_{kk} \, ln^2 Z_k + \sum_{i>f} \sum_k \beta_{ik} \, ln(P_i/P_f) lnZ_k \end{aligned} \tag{4.6}$$

with the parameters for the excluded output (i.e. feed) then derived to satisfy these homogeneity conditions. A further symmetry condition on input and output prices requires that (iv) $\alpha_{ij} = \alpha_{ji}$.

Taking the partial derivative of the profit function with respect to input and output prices (lnP_i) results in the profit share equation (and input demand/output supply equations)

$$S_i = \alpha_i + 2\alpha_{ii} lnP_i + \sum_{j \neq i} \alpha_{ij} \, lnP_j + \sum_k \beta_{ik} \, lnZ_k \tag{4.7}$$

where the profit share of an input or output, i, is given by

$$S_i = \frac{P_i Q_i}{HR} = \frac{(P_i/P_f)Q_i}{(HR/P_f)} \tag{4.8}$$

The normalised profit function and share equations are estimated simultaneously through a system of equations using Zellner's (1962) seemingly unrelated regression (SUR), which is asymptomatically more efficient than a singular estimation by least squares. In the estimation system, restrictions were imposed to ensure the coefficients in the profit function and the share equations are the same.

The short-run elasticities (with the level of quasi-fixed inputs) are estimated by

$$\eta_i = \frac{(\alpha_{ii} + S_i^2 - S_i)}{S_i}$$

$$\eta_{ij} = \frac{(\alpha_{ij} + S_i S_j)}{S_i} \tag{4.9}$$

where η_i is the own-price elasticity and η_{ij} is the cross-price elasticity of the input demand or output supply.

4.3. Data description and analysis

This section describes and presents the analyses of the simulated data used in this study. As previously mentioned, the data were obtained from stochastic production simulations of the TEA. The simulation methodology will be detailed, with relevant reference to the techno-economic model and relevant parameters. Subsequently, a summary of the data collected will be outlined followed by a description of the econometric analysis used specifically with the data. The results from the analysis will then be presented, which will lead into the discussion in the following section.

4.3.1. Production simulations

Based on the methodology description presented previously, the multi-output profit function required prices and quantities of related inputs used and outputs produced in the production process. Usually, this is obtained from industry and/or firm-level data. In this study, the production model from the TEA in the previous study was used to generate similar data for this analysis. The production scenario was re-simulated from the baseline with different parameter assumptions for prices and quantities. The former was obtained from data described in the previous chapter (Table 3.5). The quantity of inputs and outputs were varied based on changes in the growth rate and how the biomass was allocated to the three output options (biodiesel, feed, and fertiliser). The output price ranges were based on the available data also used in the previous sensitivity analysis (Table 3.6).

In terms of the inputs, there were insufficient price data for all variable inputs (e.g. hexane, potassium hydroxide, phosphoric acid). Additionally, the financial valuation and sensitivity analyses revealed that only a handful of input costs represented major contributors to the overall variable cost of the production system, namely fertilisers and utilities (including natural gas). Hence, only electricity, water, natural gas (for drying), urea, and diammonium phosphate (DAP) were included in the input variables for this analysis. The price ranges for each of these parameters were based on available data from respective sources (Table 3.8). All Australian-derived input and output prices were converted to United States dollars (US$) using the same exchange rate as in the TEA[30].

Also, given the high capital costs of microalgae (and biodiesel) production, capital maintenance costs represented a significant proportion of annual operating costs. The maintenance costs include capital maintenance and repairs, operating supplies, and insurance (Peters et al., 2003). While quasi-fixed, this cost varied depending on the input and output mix. A cost index was used to scale and introduce variability to this parameter in addition to the variability from changes in the growth rate and biomass allocation.

[30] AUD$1=US$0.905149

As there was no information on the likely form of the distributions for the prices and other data, a uniform distribution was assumed. The maximum and minimum for each parameter in the Monte Carlo simulations is given in Table 4.1.

Table 4.1: Production simulation parameters and ranges.

Parameters (units)	Baseline	Range (min – max)
Growth rate (g/m^2/day)	20	10 - 60
Proportion for biodiesel (%)	40	25 - 60
Residue for fertiliser (%)	50	0 - 100
Price of biodiesel (AUD$/l)	1.50	1.30 - 2.30
Price of feed (US$/kg)	12	2.50 - 18
Price of fertiliser (US$/kg)	12	9 - 24
Urea price (US$/t)	750.00	121.46 - 870.49
DAP price (US$/t)	550.89	227.39 - 1409.90
Natural gas price (AUD$/GJ)	7.99	5.02 - 11.56
Electricity price (AUD$/kW)	0.51	0.34 - 0.57
Water price (AUD$/t)	3.43	2.06 - 6.78
Operating cost index	1	0.80-1.20

The production scenario was simulated 5000 times in Microsoft Excel using the add-in program MCSim (Barreto & Howland, 2013).

4.3.2. Data summary

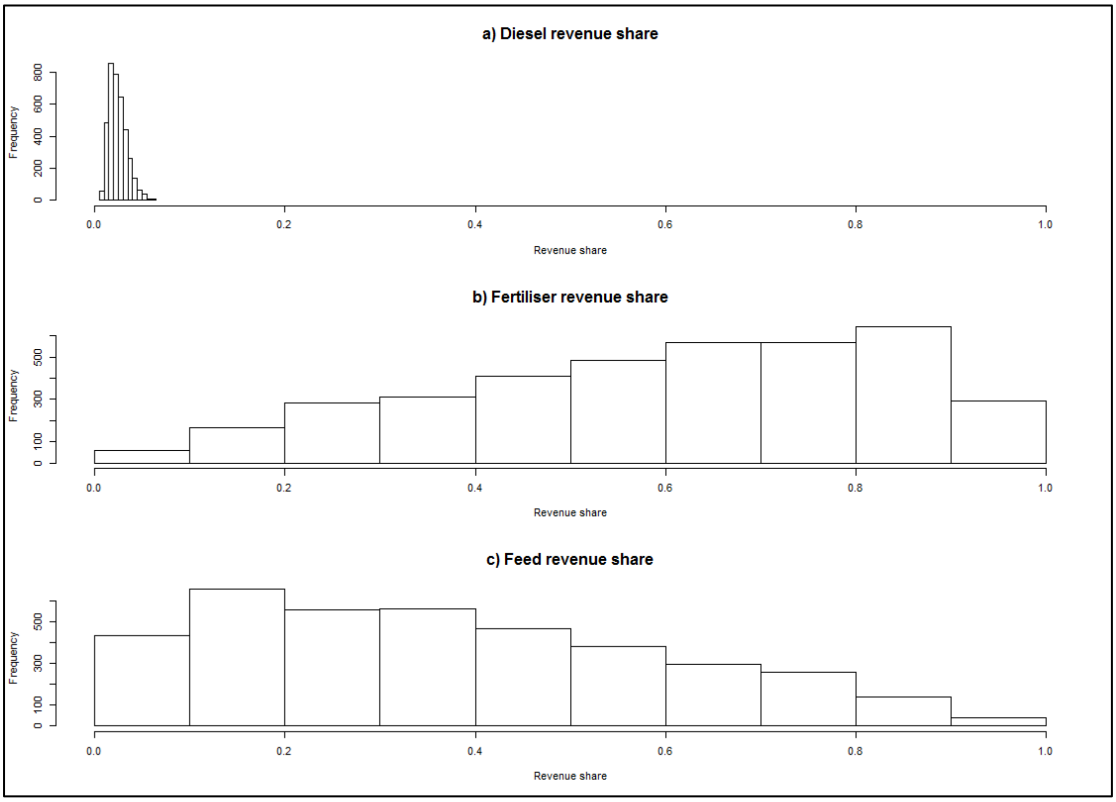
The data obtained from the Monte Carlo simulations are summarised in Appendix C. Of the 5,000 simulations, 1,219 had an overall negative NPV. These scenarios were dropped from the analysis given the realistic assumption that production would not have proceeded if the final planned NPVs were negative. The data from the remaining 3,781 simulated production scenarios that had a positive NPV and were included in the analysis are summarized in Table 4.2. The inputs were also simplified to four categories: (1) energy, (2) fertiliser, (3) others, and (4) maintenance parameters (refer to Table 4.2 for breakdown of the categories). The growth rate was included as an indicator of productive efficiency and to gauge its impacts on the profit. All the quantity (and total maintenance cost) parameters were taken as the annual amounts to ensure consistency in the profit estimation, except the growth rate. A yearly transformation of the growth parameter did not affect the estimates.

Table 4.2: Summary of simulation data used in analysis.

Parameters	Mean	SD	Min	Max
Growth rate (g/m^2/day)	38.55	13.17	10.09	60.00
Output parameters				
Price of biodiesel (US$/l)	1.63	0.26	1.18	2.08
Quantity of biodiesel (l)	3,235,213.11	1,416,389.45	520,816.24	7,240,428.81
Price of fertiliser (US$/kg)	17.25	4.20	9.01	23.99
Quantity of fertiliser (kg)	7,869,982.59	4,311,684.51	101,748.35	22,206,165.31
Price of feed (US$/kg)	11.21	4.24	2.52	18.00
Quantity of feed (kg)	7,202,999.70	4,332,273.26	120,092.32	22,032,199.33
Input parameters				
Energy parameters				
Electricity price (US$/kW)	0.41	0.06	0.30	0.52
Quantity of electricity (kW)	1,772,490.88	605,468.02	463,953.75	2,758,683.89
Natural gas price (US$/kJ)	7.48	1.72	4.54	10.46
Quantity of gas (kJ)	71,624.70	25,990.45	16,264.76	133,854.28
Fertilisers parameters				
Urea price (US$/t)	490.70	214.51	121.67	870.32
Quantity of urea (t)	3,860.03	1,318.55	1,010.37	6,007.70
DAP price (US$/t)	818.64	338.43	227.41	1,409.45
Quantity of DAP (US$/t)	930.32	317.79	243.51	1,447.94
Other input parameters				
Water price (US$/t)	3.99	1.23	1.86	6.14
Quantity of water (t)	4,251.59	2,581.63	406.01	12,821.77
Methanol price (US$/t)	457.65	152.27	200.30	719.99
Quantity of methanol (t)	332.46	145.55	53.52	744.04
Maintenance parameters				
Capital maintenance cost factor	1.00	0.12	0.80	1.20
Capital maintenance costs (US$)	40,637,948.37	10,664,740.95	15,002,380.88	72,056,835.66

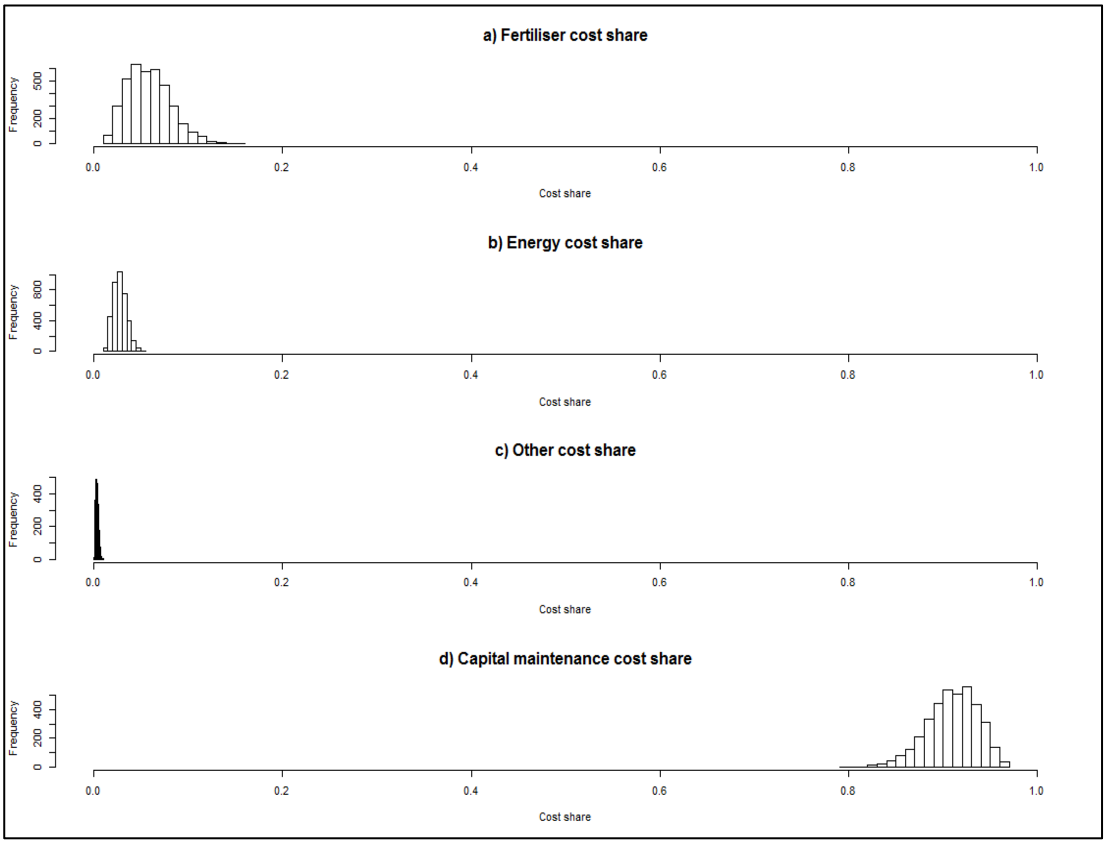
From the revenue shares (i.e. proportion of revenue from each of the three outputs) in a multi-output scenario, revenue is primarily obtained from high-value fertiliser and feed compared to biodiesel (Figure 4.1). Also, fertiliser and feed generally appeared to be substitutes in this distribution.

Figure 4.1: Revenue share of production simulations.



When comparing the cost shares (i.e. proportion of costs from the three variables), it was apparent that the majority of annual costs were accrued from maintenance costs, followed by fertilisers (urea and DAP), and then energy costs (electricity and natural gas) (Figure 4.2). The figure also suggested that the "Other costs" (that include water and methanol) were a comparably negligible proportion of the total costs. Preliminary models that included these "Other costs" also did not perform as well or illustrate the effect of price variation given its marginal cost share. Hence, to simplify the derivation of the profit function, these were then dropped, leaving three input sources: energy, fertilisers, and maintenance. These parameters also tended to form the main proportions of operating costs even in the financial valuation and sensitivity analysis study.

Figure 4.2: Cost shares from production simulations.



The profit measure was derived from subtracting the production costs (quantities multiplied by prices of the inputs and the capital maintenance costs) from the revenues (quantities multiplied by prices of the outputs). The distributions of the profit shares (i.e. proportion of profit from each output and input categories) are presented in Figure 4.3 for outputs and Figure 4.4 for inputs.

Figure 4.3: Revenues profit shares.

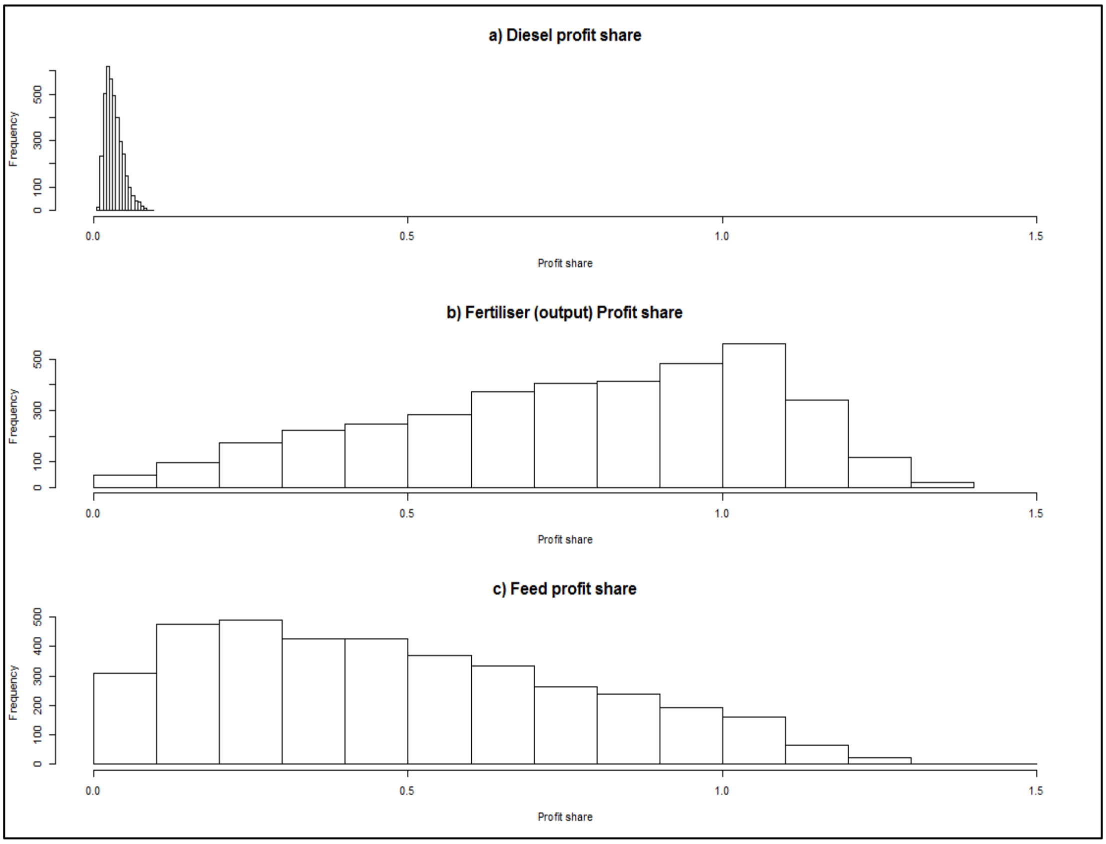
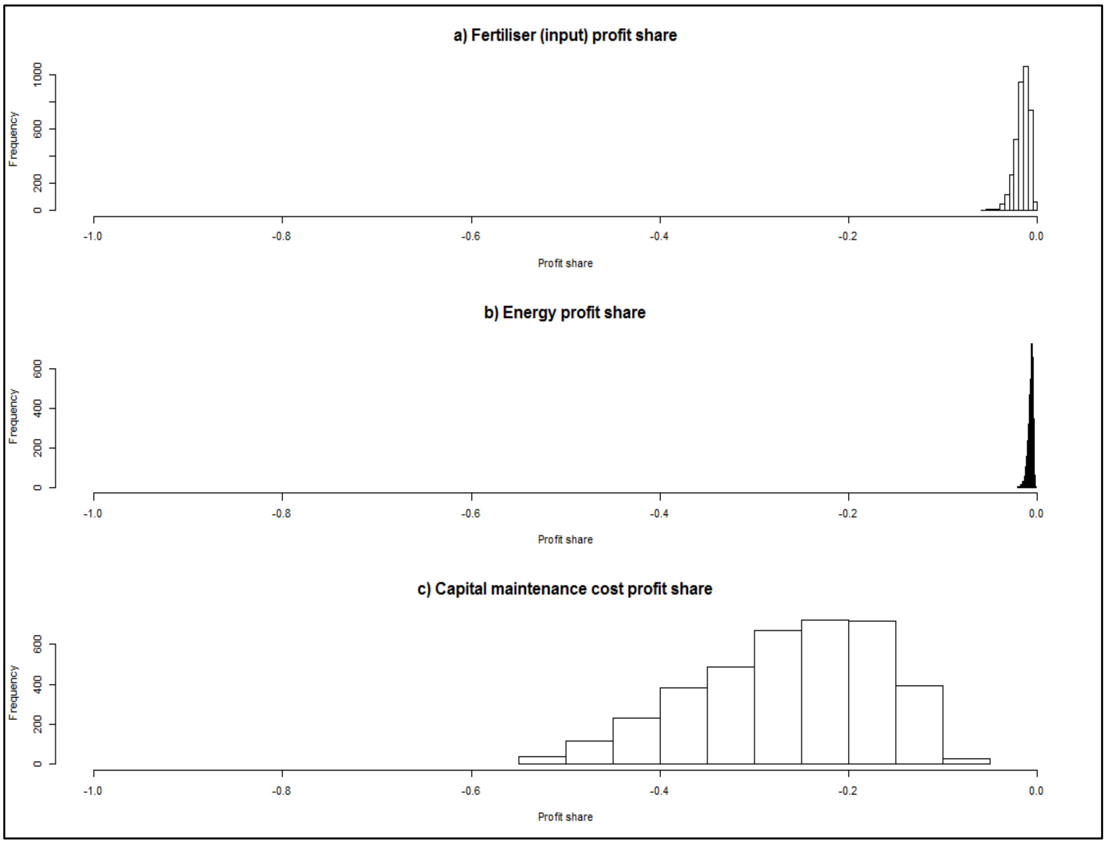


Figure 4.4: Operating costs profit shares.



For the analysis, all the variables were logged and normalised by their mean, resulting in a (logged) mean value of zero. Additionally, all price variables were normalised by feed price to ensure homogeneity, leaving only biodiesel and fertilisers as the outputs in the models. Similarly, the restricted share equations would sum to unity and as such, the share equation for maintenance was dropped in the estimation (Squires, 1987).

4.3.3. Restricted profit function estimation

The profit function was estimated using R (R Core Team, 2013) and the statistical package "systemfit" (Henningsen & Hamann, 2007) based on Zellner's (1962) SUR method of estimation. Preliminary models that were estimated only considered the fertilisers, energy, and "other" costs given the availability of available market and historical price data. However, as previously mentioned, these did not appropriately illustrate the effect from price changes, given its small share relative to capital maintenance costs that represented a significant proportion of operating costs. Hence, maintenance costs were factored into the estimation and "other" costs were dropped. The inclusion of the growth rate also improved the model fit (by AIC) and significance of the estimates.

The estimated coefficients from the estimation are given in Table 4.3. The respective estimates for feed were derived from conditions (i) to (iv) from equation 4.6 and included in the estimation output.

Table 4.3: Parameter estimates for restricted profit function.

Variable	Coeff.		S.E.
Intercept	-0.0046		0.0046
Biodiesel price	0.0320	***	0.0003
Fertiliser(out) price	0.7704	***	0.0039
Feed price	1.1980	***	0.0134
Energy price	-0.0078	***	0.0002
Fertiliser(in) price	-0.0164	***	0.0005
Maintenance price	-0.9770	***	0.0129
Biodiesel price^2	0.0119	***	0.0005
Fertiliser(out) price^2	0.1329	***	0.0124
Feed price^2	1.0445	***	0.0591
Energy price^2	0.0010	***	0.0002
Fertiliser(in) price^2	-0.0058	***	0.0007
Maintenance price^2	-0.1424	***	0.0249
Biodiesel price x fertiliser(out) price	-0.0366	***	0.0017
Biodiesel price x feed price	0.0078	***	0.0026
Biodiesel price x energy price	0.0018	***	0.0005
Biodiesel price x fertiliser(in) price	-0.0009		0.0006
Biodiesel price x maintenance price	0.0160	***	0.0017
Fertiliser(out) price x feed price	-0.2126	***	0.0278
Fertiliser(out) price x energy price	0.0069	***	0.0013
Fertiliser(out) price x fertiliser(in) price	0.0227	***	0.0032
Fertiliser(out) price x maintenance price	0.0858	***	0.0251
Feed price x energy price	-0.0023		0.0021
Feed price x fertiliser(in) price	-0.0059		0.0046
Feed price x maintenance price	0.0595	*	0.0349
Energy price x fertiliser(in) price	0.0004		0.0005
Energy price x maintenance price	-0.0077	***	0.0013
Fertiliser(in) price x maintenance price	-0.0104	***	0.0032
Growth rate	0.9324	***	0.0091
Growth rate^2	-0.0781	***	0.0123
Biodiesel price x growth rate	0.0033	***	0.0006
Fertiliser(out) price x growth rate	-0.0041	***	0.0011
Energy price x growth rate	-0.0012	**	0.0005
Fertiliser(in) price x growth rate	0.0089		0.0108
Maintenance price x growth rate	0.0756	***	0.0292
Adj. R^2			
Profit function	0.864		
Biodiesel share equation	0.320		
Fertiliser(out) share equation	0.315		
Energy share equation	0.307		
Fertiliser(in) share equation	0.471		
AIC	-98075.3		
Log. Likelihood (d.f.=43)	49080.7		

'***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%

In terms of model fit, the model shown in Table 4.3 has a high adjusted-R^2 of 0.864, suggesting the model was able to account for 86% of the variability in the simulated profits. The adjusted R^2 for the individual share equations[31] are comparably lower, but are consistent with other empirical studies in the literature (Asche et al., 2007; Pascoe et al., 2011) and may not necessarily be an indication of poor model performance. Most of the coefficients were significant at least at the 5% level, with the majority being significant at the 1% level.

The signs of the coefficients were also as expected, with outputs having a positive relationship with profit and inputs having a negative relationship. Expectedly, the magnitude of coefficients for feed and fertiliser outputs were much higher than biodiesel, pointing to the greater positive impact these products have on profit compared to biodiesel. In addition, the effects of maintenance cost fluctuations expectedly had the highest impact of profit, followed by fertiliser inputs, and energy.

The impact of growth rate on profit was also significant and positive as expected. However, the most notable finding from this estimation was that the interaction term of growth rate and biodiesel price had a highly significant positive relationship with profits, as compared to a similar interaction between growth rate and fertiliser output. This would suggest that increases in growth rate would positively impact the profitability of biodiesel production compared to fertiliser output; this is a key consideration on the long-term objectives of a microalgae producer.

4.3.4. Price elasticities

Elasticities were estimated to determine how changes in prices might affect a producer's decisions in input demand and output supply. The short-run own and cross-price elasticities

[31] Share equation estimations are presented in Appendix D. The coefficients are represented accordingly in the profit function based on the restrictions outlined in equation (4.6).

were derived using the functions given in equation 4.9, and are shown in Table 4.4. The derived own-price supply elasticities for biodiesel and fertiliser output were both highly significant at 1% but unexpectedly negative. This finding suggested that as price of these goods increased, the quantity supplied decreased, which goes against the fundamental economic law of supply (Hubbard, Garnett, Lewis, & O'Brien, 2013). However, the respective coefficients of both profit functions and share equations were expectedly positive and similarly highly significant. The inconsistency of elasticities could be possibly attributed to the disproportionate revenue shares between biodiesel and other outputs. The own-price elasticities for feed and all inputs were highly significant and had the expected signs; with the former being positive and latter being negative. The elasticity of energy demand to price was the highest and suggested it was relatively elastic i.e. the change in quantity demanded is higher than the change in price (Hubbard et al., 2013). Both the fertiliser (in) and maintenance costs were relatively inelastic.

In examining the significant cross-price elasticities, some expected results are observed. As the biodiesel prices increased, the output supply elasticity indicated a complementary increase in maintenance expenditure. This effect likely occurred when the increase in biodiesel production increased investment in biodiesel production (cell-separation and transesterification) equipment that would require high annual maintenance costs. Similarly, the cross-price elasticity between the maintenance price and biodiesel output supply was negative, and conversely positive for fertiliser (output) and feed. This result could be interpreted as a substitution from biodiesel to fertiliser (out) and feed as the maintenance cost increased, given the established complementary relationship between maintenance costs and biodiesel. Likewise, fertiliser (out) and feed prices had negative cross-price relationships with maintenance demand (i.e. as the prices of these outputs increased, the demand for maintenance decreased). Again, this effect was due to the substitution of biodiesel for the other outputs, which affects maintenance demand accordingly.

Energy prices had negative cross-price elasticity with biodiesel supply and a positive elasticity with feed supply. This finding was initially unexpected given that the energy price included the natural gas price, which should have a complementary (negative) relationship with feed. However, it could also be due to the effect from electricity prices, which powered the entire production system. Hence, if energy prices increased, biodiesel output was substituted for higher-revenue feed output to maximise profits. Therefore, the effect from the latter could be assumed to be greater than the former i.e. the impact of electricity price increases to the substitution from biodiesel to feed was greater than the impact from natural gas price increases resulting in the opposite substitution.

Table 4.4: Own† and cross-price elasticities.

	Output supply						Input demand					
Prices	Biodiesel		Fertiliser(out)		Feed		Energy		Fertiliser(in)		Maintenance	
Biodiesel	-0.597	***	-0.367	***	0.734	***	0.048	***	-0.043	***	0.236	***
Fertiliser(out)	-0.015	***	-0.056	***	0.213	***	0.001		0.013	***	-0.154	***
Feed	0.049	***	0.339	***	1.649	***	-0.013	***	-0.028	***	-0.140	*
Energy	-0.200	***	-0.123		0.806	***	-1.136	***	-0.066		0.739	***
Fertiliser(in)	0.086	***	-0.632	***	0.836	***	-0.031		-0.653	***	0.376	*
Maintenance	-0.029	***	0.451	***	0.256	*	0.021	***	0.023	*	-0.727	***

†Shaded boxes represent own-price elasticities. '***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%

4.4. Discussion

4.4.1. Findings and contributions from analysis

The use of stochastic simulations in the production literature for microalgae is not necessarily novel, but often its use is limited to non-econometric aims. These include studies on risk analysis (Richardson et al., 2012) or analysis into different production outcomes (Delrue et al., 2012; Fortier et al., 2014; Richardson et al., 2014). Although such analyses illustrate important information to a potential producer or investor, the findings from an economic perspective were limited. In particular, production-based simulations do not highlight the impact of price fluctuations of multiple parameters on feasibility or profitability. Furthermore, when considering a multi-output production system, using such simulations does not demonstrate the importance of the output mix to profitability.

The results from this study did raise some key findings that would have been missed in a typical production analysis or TEA. These TEA and sensitivity analyses can identify individual parameters that influence the NPV or profit. However, the estimation of the profit function in this study helped to illustrate the relationship between input and output prices with the input demand and output supply of the production system. This was especially useful in a multi-output production system, as it would help to illustrate the output mix that can maximise profits for a potential producer.

Firstly, the analysis found that profits were heavily determined by revenues, with costs representing relatively marginal proportions. One exception was large annual maintenance costs that were mainly dependent on allocation to biodiesel. This finding was due to the costly capital inputs of biodiesel production contributing to significant annual costs. The profit function estimation also illustrated the highly significant impact of growth rates on profitability, almost as much as the shifts in maintenance prices. Most interestingly, an increase in growth rates was shown to have a positive impact on the profitability of producing biodiesel, as compared to the negative relationship of the interaction of fertiliser output with the growth rate. This would indicate that future developments in the growth rate of the microalgae strain would benefit a biodiesel producer in terms of profitability of the system.

As noted previously, Davis et al. (2011) suggested that algae biofuel economics might be improved through development of multi-output production systems, with the spent algae biomass being used for more valuable co-products beyond biogas for power generation. The results of this study suggested that shifting emphasis from algae for biodiesel to fertiliser and feed outputs was more likely to result in higher levels of profitability than focusing on biodiesel alone. This is counter to many of the main aims of recent algae research, which has algae-based biofuels as a primary focus. While ecological benefits of microalgae biofuels may be substantial, the economics has suggested that more valuable uses of the biomass exist, at least given current production technologies. The potential for these alternative algae-based industries has not received much consideration previously.

4.4.2. Implications for microalgae biodiesel production

This study further substantiated the assertions that biodiesel production from microalgae biomass was not the most viable or profitable use of the biomass. The previous study in Chapter 3 illustrated the negative impacts of high capital costs from transesterification equipment on longer-term NPV. This study found that short-term (annual) profitability was largely affected by capital maintenance costs, which accrued from costly biodiesel processing equipment. Hence, producing the non-energy products contributed a larger profit share. Respective price increases were also more influential on profits for these products compared to biodiesel. Therefore, initial investment in microalgae production would be more influenced by fertiliser and feed production (and possibly other non-energy products).

This outcome would not necessarily represent the end of microalgae biofuel development but instead, a potential transitionary step. In addition to the high profits from microalgae-based products, the integration of microalgae production with existing industries could still garner the bio-fixation benefits of carbon and high-nutrient effluents. These substantial potential profits and external benefits from production could justify private and public investment in production facilities. This allows establishment of infrastructure and relevant supply chains for cultivation. In the longer term, developments to the growth rate of the microalgae biomass (as shown in the results of this study) and also cost-efficiency of the biofuel processing technologies would need to be realised to encourage adaptation of the production systems to produce a greater quantity of biofuels, eventually making it the primary objective of the system.

4.4.3. Limitations and further research

The estimation of a multi-product profit function is often estimated using data from existing production and industries. However, the lack of established microalgae biofuel and multi-output industries resulted in the analysis depending on simulated production data. The price and cost assumptions, as well as production processes used in the model, were based on existing conditions and technologies in what is still an infant industry. As technology for biodiesel production becomes more cost efficient, this is likely to alter the revenue and profit shares. Nevertheless, at the current state of technology, the production model used for simulations (as detailed in Chapter 3) represents an ideal model of publically available data and parameters, in addition to being the only known production model of multiple outputs for microalgae. Thus, the results remain valid at the current stage of production[32].

4.5. Conclusion

The aim of this study was to determine the effect of input and output price fluctuations on the profitability of a microalgae production system with multiple outputs. This objective was accomplished by simulating production scenarios using the TEA model from Chapter 3 and estimating a multi-product profit function.

The results indicated that non-energy products heavily influence profits from microalgae production. The results suggest that not only do these products improve profitability of biodiesel production, they may be more profitable than biodiesel itself. In particular, the elasticity of a higher moisture feed was found to have a significant positive impact on profits. Also, the study found that the elasticity of energy was the highest among inputs, signifying the higher substitutability of energy usage through selection of products requiring lower energy inputs i.e. feed.

The methodology and results added new information to the economic literature on microalgae biofuels. The results would be informative to potential investors and producers of microalgae, particularly in considering multiple outputs. The findings may also inform policy focused on supporting production investment.

[32] The analysis could also be improved through technical improvements of the production model. This was elaborated upon in section 3.5.3.

Chapter 5. Consumer preferences for biofuels

5.1. Introduction

As a close substitute for petrol and diesel, biofuels have the potential to play a larger role in the transport fuel market in the near future through fuel blending and related mandate policies. However, the review of biofuels in 0 has suggested that conventional biofuels produced from terrestrial agriculture-based feedstocks can raise the economic costs of increased biofuel usage, particularly in terms of increased competition for crops and agricultural resources. This may justify investment in alternative biofuel feedstocks, like microalgae, that avoid such issues and also benefit from bio-fixation of waste streams from other industries.

However, the use of production costs to gauge price and market share fails to accurately forecast demand from potential consumers. This is because production-based estimates only give an indication of the minimum price for the production to be financially feasible i.e. the supply side. This is then used in comparison to the current selling prices of fuel that utilise regular (fossil) fuel or conventional biofuel demand, which is not entirely representative of the likely demand for microalgae biofuels. This supports Brownstone, Bunch, and Train (2000), who state that current markets would not have sufficient information about consumer preferences for inexistent markets, rendering estimates inappropriate. Speculation of the likely markets for alternative biofuels will be ill-informed, which can be detrimental to both public and private investment.

More importantly, given the likelihood of biofuels further penetrating the fuel market through policy support, attention must be given to the external benefits of different biofuel feedstocks.

Often, justification for biofuel-related policy is outside of improvements to mileage and fuel performance. Instead, fuel security, industrial development, and environmental benefits are tied to increased policy support (O'Connell et al., 2007). Hence, the value of the associated external benefits (also known as positive externalities) must be then quantified to gauge the efficiency of biofuel-related policies. The literature has highlighted the clear benefits of third generation biofuels over their first and second-generation counterparts. However, there has been no economic analysis on the value of these benefits that could be used to justify the need for policy support.

The aim of this study was to derive the economic value of biofuels through analysing consumer preferences and estimating the economic value of the externalities from biofuel consumption. This was accomplished through a non-market valuation technique known as Discrete Choice Experiments. This methodology allowed for estimation of marginal values for specific attributes associated with alternative biofuels, particularly from microalgae, as highlighted in Chapter 2 of this thesis. Consequently, these results were used to illustrate economic value of different biofuel feedstocks from a broader perspective, quantifying the benefits of different feedstock generations. The majority of the literature assessing consumer preferences in transport has focused on practical aspects of the fuel. This study represented a novel contribution in identifying the benefit values for the externalities of biofuels.

The following section will present a review of non-market valuation and identify its importance to the study design. Then, a description of the methodology will be detailed, including theoretical underpinnings, econometric specification, and experimental design. Subsequently, a description of the survey data and econometric results will be presented.

Finally, this chapter will be concluded with a discussion of the implications of the results, limitations, and recommendations for further study.

5.2. Review of non-market valuation

This study utilised a non-market valuation technique, Discrete Choice Experiments (DCEs), to estimate the value of the positive externalities associated with alternative biofuels. This section will discuss the literature surrounding non-market valuation before detailing the two general descriptions for these techniques i.e. revealed preference and stated preference. Emphasis will be given to description of the stated preference techniques, being relevant to this study. Subsequently, discussions will be presented on the preference of DCE for this study and relevant limitations of this technique that can be addressed. Finally, previous literature that attempted to estimate the non-market value of alternative fuels will be discussed, highlighting the gap that this study will address. The findings from this review not only justified the methodology used, but also shaped the design and analysis that will be presented subsequently.

5.2.1. Non-market valuation

It is often the case in decision-making, particularly for policy, that the values of certain goods or services are not accounted for explicitly in the market. This often occurs when there is an external benefit or cost, known collectively as externalities, from consumption that is not captured in the market price. This can result in inefficient resource allocation. Non-market valuation techniques are a common method for estimating the economic value of such externalities (Haab & McConnell, 2002). These values can then be incorporated into more explicit cost-benefit analyses, and designing appropriate policy frameworks. Non-market valuation has more often been used in the environmental contexts, particularly with natural resources. These techniques are broadly classified into revealed preference and stated preference methods.

5.2.1.1. Revealed preference methods

Revealed preference (RP) methods are used to estimate use-values that are not captured directly from market data. RP methods are based on observable and actual choices for utility maximization (Parsons, 2003). Preferences of non-market values are determined indirectly through consumption of representative market goods (Freeman, 2003). More fundamental RP methods include analysis of market or census data (Brownstone et al., 2000). Incorporation of user-response consumption preferences have been increasingly applied to RP studies such as in food consumption (Myrland, Trondsen, Johnston, & Lund, 2000) and education (Jacob & Lefgren, 2007). Recent examples pertaining to ecosystem services include user-value for natural resources estimated using the travel cost method (TCM) (Doshi & Pascoe, 2013; Martínez-Espiñeira & Amoako-Tuffour, 2008, 2009; Pascoe et al., 2014), and the impact of floods on house prices estimated through hedonic pricing (HP) (Bin & Landry, 2013; Pryce, Chen, & Galster, 2011).

RP methods have been well established and extensively applied in the context of non-market valuations. However, there are key limitations to the application of these methods to ascertain non-market values. Studies in ecosystem valuation highlight the inability to account for non-use and passive use values. However, the main issue with regards to the context for this study is the inability for RP methods to assess non-market values for hypothetical situations/markets or new products (R. T. Carson, Flores, & Meade, 2001; Louviere, Hensher, & Swait, 2000). The lack of established markets or representative market goods results in the inability to derive estimates (Bunch et al., 1993). Also, attempting to estimate proxy values from existing markets is largely uninformative in such cases (Bennett &

Blamey, 2001a). This has been the case for more conventional alternative energy sources despite the relative uptake, due to the comparably lower acceptance of alternative energy compared to fossil fuels (Pancholy, Thomas, Solís, & Stratis, 2011). It becomes more apparent for microalgae-based fuel alternatives that do not have any commercial markets.

5.2.1.2. Stated preference methods

Stated preference (SP) methods are valuation techniques that determine the value of a good or service through reported responses to (hypothetical) changes or scenarios (Bennett & Blamey, 2001a). Individuals are assumed to account for information regarding various available scenarios of a particular decision-making problem. These agents then evaluate the 'quality' of each alternative based on various attributes, and make trade-offs on levels and positions of these attributes in selecting one of the alternative scenarios (Adamowicz, Louviere, & Swait, 1998b). Thus, individuals derive utility from the bundle of characteristics or attributes rather than the good or service itself[33] (Louviere et al., 2000). The individual choices are then modelled to determine the marginal values of the specific good, service, or attribute, based on the survey sample. These responses are grounded on economic principles of rational choice and utility maximisation.

The theoretical underpinnings of SP methods are based on Random Utility Theory. Initially proposed by Thurstone (1927), this theory assumes that an individual makes choices to maximise his utility based on two types of elements, systematic (known and observable), and random (unknown and unobservable); subject to constraints e.g. income and time endowments. Both good/service characteristics and individual differences (e.g. demographics) form the systematic, explanatory components of the behavioural choices, outside of other unknown factors captured in the random component. As responses are

[33] This overview of stated preference theory is an evolution from early definitions of conjoint analysis, particularly by Green and Srinivasan (1978).

generally based on a finite number of alternative scenarios, SP methods are often modelled based on probabilistic models (e.g. probit, logit, and multinomial logit).

Stated preference valuation studies most often utilize two types of methodologies[34]: (1) contingent valuation methods (CVM) and more recently, (2) discrete choice experiments (DCE[35]).

Contingent valuation method

Initially proposed by Ciriacy-Wantrup (1947), CVM analyses how much respondents are willing to pay (or accept) for a change in the quality/attribute of a good or service through scenario-based surveys. The estimated economic values for specific attributes are "contingent" on those highlighted in each listed scenario (R. T. Carson, 2011). The types of questioning employed in CVM is diverse across the studies; they can either be open-ended (e.g. how much a respondent will be willing to pay) (Alvarez-Farizo, 1999), referendum-styled (is respondent willing to pay $X?) (Cameron & Huppert, 1991), or through bidding (listing progressively increasing WTP values until the response rejects) (Yu & Abler, 2010). While the use of such direct survey methods to derive demand schedules was much debated among economists, there has been some admission in the validity of such surveys due to the ability to capture (complete) non-market monetary values and non-use values (Hanemann, 1994); as evident in the much quoted statistic of over 7500 studies across 130 countries catalogued by R. T. Carson (2011).

[34] Conjoint analyses (CA) are not addressed in this review as a SP method due to it being based purely on mathematical systems rather than individual preferences. However, reference to past CA studies will be discussed if they provide insight into the study or are relevant examples outside of the economics discipline. There has been discussion into how some CA studies resemble DCEs (i.e. Louviere, Flynn, & Carson, 2010) or that DCEs are an evolution of CAs (Bennett & Blamey, 2001a).

[35] Taking the cue from R. T. Carson and Louviere (2011), the term DCE is used rather than the more common 'choice experiment' to avoid confusion with the latter's use in other disciplines, the underlying theories and assumptions, and the interpretation of estimates.

The open-ended variant is said to result in inflated WTP estimates due to the lack of realistic boundaries for a respondent both in the laboratory (Neill, Cummings, Ganderton, Harrison, & McGuckin, 1994) and field setting, which Loomis, Brown, Lucero, and Peterson (1996) attempted to reduce in the former through more stringent survey questions. However, there has been some evidence that the open-ended CVMs can result in lower WTP estimates compared to bounded varieties (T. C. Brown, Champ, Bishop, & McCollum, 1996). The bidding-styled CVM is largely similar, in that the respondent is not bounded by his/her response for a WTP. The use of a referendum-styled CVM is the most popular variant in the literature, where respondents are given hypothetical choices of paying a stated amount for a particular good/service or change in quality, most often done with dichotomous choices. The aggregate WTP is then estimated using random utility models (RUM) using limited dependent variable (LDV) regressions i.e. probit and logit for dichotomous choice, and multinomial variants for multiple alternatives.

Several limitations have been highlighted in regards to the use of CVM. These pertain to how responses might be invalid or subject to bias due to respondents misrepresenting their preferences, 'yea saying', being insensitive to the scope, or not reflecting the accessibility to substitutes (Bennett & Blamey, 2001a). These have resulted in criticism of the methodology (Portney, 1994). Also, issues regarding the survey design and administration (R. T. Carson, 2011; R. T. Carson et al., 2001) have suggested the need for alternative methodologies.

Discrete choice experiments

Discrete choice experiments (DCE) estimate the probability of choosing from a given set of alternatives, known as a 'choice set', where the individual receives the highest perceived utility based on both known and unknown elements (Train, 2009). The alternatives are characterised by a set of attributes at different levels (Adamowicz et al., 1998b) and considers individuals making trade-offs across multiple attributes simultaneously (Bennett & Blamey, 2001b). The marginal utility from each attribute can then be estimated through analysis of these trade-offs (Adamowicz et al., 1998b; Hensher, Rose, & Greene, 2005a). The referendum-styled (dichotomous) CVM is largely similar to DCE techniques. However, unlike the former, DCE employs the use of multiple alternative hypothetical scenarios/choices with varying attribute levels marked with related WTP values, and the specific inclusion of a status quo or 'no-choice' option to avoid issues of forcing (Rolfe & Bennett, 2009). The responses are then estimated using multinomial models and the WTP value for specific attributes can be derived from regression estimates. Although there are methodologies (e.g. conjoint analyses) in non-economic studies that employ a similar design (e.g. Green & Srinivasan, 1978, 1990), DCEs are specifically based on economic theory and potentially help to elicit choice preferences rather than just estimate aggregate preferences specific for the sample (Adamowicz, Boxall, Williams, & Louviere, 1998a; Louviere et al., 2010).

DCEs were developed to overcome methodological limitations in transport choice studies (Louviere, 1981; Louviere & Hensher, 1982) and they continues to be a tool in this field (Hensher, 1994; Hensher, Barnard, & Truong, 1988; Kroes & Sheldon, 1988). Since then, the use of DCEs in environmental economics literature has been increasing, particularly in conjunction with non-market valuation of natural resources. Some examples include valuation of coral reefs (Ngazy, Jiddawi, & Cesar, 2005; Wattage et al., 2011), national parks (Boxall & Adamowicz, 2002; Chaminuka, Groeneveld, Selomane, & van Ierland, 2012; Juutinen et al., 2011), and forests (Boxall & Macnab, 2000; Christie, Hanley, & Hynes, 2007; Lehtonen, Kuuluvainen, Pouta, Rekola, & Li, 2003). They have also been used to derive consumer preferences for environment-related activities like recreational fishing (Breffle &

Morey, 2000; Chen & Cosslett, 1998; Provencher, Baerenklau, & Bishop, 2002; Provencher & Bishop, 2004; Train, 1998), rock climbing/hiking (Scarpa & Thiene, 2005), and diving at coral reef sites (Doshi et al., 2012; Ngazy et al., 2005; Parsons & Thur, 2007). More relevant use of DCEs in energy and fuel choice will be discussed further in this section.

5.2.2. Benefits and limitations of discrete choice experiments

There are a number of key benefits of DCEs over CVMs as an SP method of non-market valuation, especially in the context of alternative energy in transport and hypothetical goods. The availability of a detailed account of respondent trade-offs and preferences allows for estimating attribute-specific estimates (Bennett & Blamey, 2001b). These preferences can then be applied to alternatives that may not be specifically represented in the experiment e.g. the marginal WTP for emissions reduction can be applied to any similar fuel choice. These 'decomposed' estimates can also be used beyond the scope of the DCE, such as in benefit transfer (Morrison, Bennett, Blamey, & Louviere, 2002) and policymaking (Bennett & Blamey, 2001b). Also, DCEs reduce the severity of yea-saying, and scope and framing issues that plague SP methods compared to CVM (Bennett & Blamey, 2001a, 2001b; Rolfe, Bennett, & Louviere, 2000, 2002). As an SP method of non-market valuation DCEs are subject to hypothetical bias (Hensher, 2010). However, studies have suggested methods where DCEs can reduce this bias relative to other SP methods (Morrison, Blamey, Bennett, & Louviere, 1997; J. J. Murphy, Allen, Stevens, & Weatherhead, 2005).

Nonetheless, DCEs are also subject to limitations. A major issue is the additional cognitive burden that the experiment places on respondents. This is due to the relatively more complex design of DCEs compared to other methods, including CVM. This can result in the respondent becoming confused, fatigued, or frustrated, resulting in improper weighing of the attributes and making inaccurate trade-offs (Bennett & Blamey, 2001b). Respondents might also not agree (or protest) with the premise of the experiment and/or alternatives, resulting in a similar issue of inaccurate trade-offs and choices (Bennett & Adamowicz, 2001). These two limitations can manifest themselves through respondents either ignoring any number of the attributes (including all) or making choices randomly, or choosing the same option consistently across the experiment. This results in inaccurate and biased estimates. However, accounting for these issues through the experiment design and modelling can reduce and alleviate them.

Also, despite reducing framing and scope issues from other SP methods, DCE can still be exposed to them. In terms of the former, the context-setting pre-experiment briefing may over-inform respondents and result in upwards bias to estimated values (Rolfe et al., 2000). However, this unrealistic information overload is likely the result of difficulties in capturing all relevant issues within the limited choice set (Bennett & Blamey, 2001b), causing practitioners to add complexity and deviate from reality in experiment and survey designs. The hypothetical nature of DCE also leaves it susceptible to issues of scope insensitivity, with respondents showing the same WTP for attributes at different levels due to an indifference for increasing levels beyond a certain point (Frontuto, Dalmazzone, Vallino, & Giaccaria, 2017; Rolfe et al., 2000). The framing issue can be accounted for through a survey and experiment design that appropriately frames the context in a realistic scenario and avoid over-information. The issues from scope insensitivity were assumed to less apparent in this context as the levels were not defined by areas and years, which is more apparent in natural resource-based DCEs.

Finally, like all SP methods, DCEs are subject to potential inflated WTP estimates, which may not reflect actual WTP, due to hypothetical bias (Hensher, 2010). There have been a number of ways suggested to reduce this effect including benchmarking prices to actual prices (Bergmann, Hanley, & Wright, 2006; Roe et al., 2001) or introducing 'cheap talk' scripts to reduce potential inflated WTP estimates (Carlsson, Frykblom, & Johan Lagerkvist, 2005; Van Loo, Caputo, Nayga Jr, Meullenet, & Ricke, 2011). The latter includes a script informing respondents about avoiding overestimating their value of attributes and also to consider their own household budgets where relevant. However, the context of this study, the lack of a second and third-generation biofuels in the Australian transport fuel market makes benchmarking to related biofuel prices impossible. Also, it would be presumptuous to suggest to responses that WTP would be overstated given that a DCE on biofuel externalities has not been previously addressed in the literature. This would be addressed in the discussion if the results suggest an overestimation of WTP as a possible issue.

5.2.3. Stated preference studies in alternative energy

There have been comparatively few studies using non-market valuation in the context of renewable fuels and energy[36] (Menegaki, 2008). These studies have generally employed SP methodologies to estimate the WTP for the energy source and/or the associated attributes. Studies pertaining to consumer preferences in renewable energy are based on the notion that the success of the relatively more expensive alternatives is dependent on voluntary choice to pay more, given the environmental benefits, and sufficient marketing and information of these benefits (Roe et al., 2001); this is true especially with findings that involuntary programs for green energy yielded a negative WTP (Borchers, Duke, & Parsons, 2007). A number of such studies have been conducted with regards to the use of 'green' or biomass-based electricity in the USA (Roe et al., 2001; Scarpa & Willis, 2010)[37], Japan (Nomura &

[36] Menegaki (2008) gives a comprehensive review of valuation studies for alternative energy, utilising economic, financial, and engineering/ecological techniques.

[37] Roe et al. (2001) were able to compared CVM estimates with RP estimates through hedonic pricing due to the presence of a green electricity market in the US. The study found that estimates of WTP were comparable and complementary, with consumers being priced at levels similar to their value of the emissions benefits.

Akai, 2004), Korea (Ku & Yoo, 2010), and the UK (Bergmann et al., 2006; Longo, Markandya, & Petrucci, 2008). Such studies have generally concluded that there is sufficient evidence of consumer support for renewable energy, if at least within the sampled area. Higher estimates for WTP were attributed to the income demographics and political beliefs (Bergmann et al., 2006; Longo et al., 2008). There is also sufficient indication that knowledge of relevant fuels' potential and externalities can improve the WTP for these renewables. Hence, exposure to green marketing is a significant factor in consumer preference for alternative energy (Nomura & Akai, 2004; Roe et al., 2001; Zografakis et al., 2010).

In terms of transportation and fuel consumption, SP studies have been conducted to estimate preferences in fuels, vehicles, and blending policies, the last of which being implemented mostly in the USA. The SP methods, in particular, have been utilised due to their ability to capture preferences in hypothetical scenarios (Hensher et al., 1988). The majority of these studies using CVM have found a positive WTP value for renewable fuels (Jeanty & Hitzhusen, 2007; Petrolia et al., 2010; Solomon & Johnson, 2009). Similar to green electricity, there were specific demographic characteristics that could determine the likelihood and quantity of WTP such as knowledge and perception of renewable energy, climate change beliefs, and political ideologies (Jeanty & Hitzhusen, 2007; Li, Jenkins-Smith, Silva, Berrens, & Herron, 2009; Solomon & Johnson, 2009). With CVMs being more common in this context, the attributes of the specific fuels are not often an issue of study in non-market valuation of alternative transport fuels.

An early DCE study by Bunch et al. (1993) indicated that among the attributes to determine consumer support for fuel choice were the availability of the related fuel (i.e. refuelling stations), relative fuel cost to gasoline, and also the emissions; the latter of which was found to compensate lower levels in availability and relative price. This importance of the vehicle and fuel characteristics, including mileage and performance, were echoed in later works (Dagsvik, Wennemo, Wetterwald, & Aaberge, 2002; G. O. Ewing & Sarigöllü, 2000; Fimereli & Mourato, 2009; Giraldo, Gracia, & Do Amaral, 2010; Khachatryan, Joireman, & Casavant, 2011). These studies emphasize the importance of more practical aspects of fuels (i.e. refuelling ease, mileage, performance) rather than environmental (often limited to emissions) attributes.

Consumers have been found to attach significant values to environmental-related benefits (Mabit & Fosgerau, 2011). However, these studies still maintain the consumer preference of green vehicles/ alternative fuel vehicles only when practical aspects are similar. A CA study by Ahn et al. (2008) found a contradictory preference of their Korean sample for gasoline-powered vehicles when practical characteristics were constant. However, the authors acknowledge that this is partially due to the lack of specific attributes for alternative energy, and the relative lack of knowledge of green vehicles relative to conventional fossil fuel vehicles.

More recent SP studies on biofuels have attempted to account for broader economic impacts of biofuels. A paper by Susaeta, Alavalapati, Lal, Matta, and Mercer (2010) accounted for effects on biodiversity from biofuel choice but did so using a dichotomous choice experiment. This can result in the loss of information on trade-offs of the different attributes. They found that heterogeneous WTP estimates for biodiversity and emission improvements were based on actual fuel prices and socioeconomic variables. Khachatryan et al. (2011) included attributes addressing impacts on food prices but they allowed a status quo choice of regular gasoline. They found that respondents who were pro-environment and concerned about long-term effects of current decisions had a greater preference for biofuels with broader benefits to the environment and food supplies. However, the marginal value of impacts to food price was not estimated. Conversely, a more recent study by Kallas and Gil (2014, 2015) also attempted to account for effects on food prices but they employed an open-ended response for their price variable. This approach can result in a disconnect from the attributes being investigated. They found that there was a negative relationship between impact to food (specifically bread) price and utility, but stressed that pre-survey perceptions of biofuel suitability had greater influence over consumer WTP.

These studies highlight some important attributes to consider with regards to the consumer preference study in this thesis. In addition to the WTP for an alternative fuel, attributes pertaining to fuel performance and more importantly, associated externalities can determine the consumer preference for one fuel-type over another. However, the latter can represent a source of hypothetical bias. The majority of past DCE studies for alternative transport fuel focused on preferences based on practical aspects and did not include the effect of individual demographic characteristics. These demographic variables have been found to be significant factors in studies of alternative fuels outside of the transport context and in CVM analyses. In addition to individual income, variables identifying knowledge of renewable fuels, political ideologies, and beliefs in climate change can also potentially account for the likelihood of a representative consumer having a positive WTP for alternative transport fuels.

5.2.4. Approach for experiment design

This study attempted to build from the choice modelling work on biofuels, particularly by Susaeta et al. (2010) and Khachatryan et al. (2011), by accounting for trade-offs in food prices and biodiversity, as well as emissions. However, this study looked specifically at the trade-offs between alternative biofuel types without a petroleum-based alternative. This was based on a hypothetical but realistic scenario in Australia, of a mandated biofuel policy where biofuel-blends would replace regular petrol/diesel. Respondents would therefore have to choose between different biofuels to support, based on the above mentioned attributes. Assuming the practical aspects of the biofuels (mileage, performance, refuelling access) would be the same, the corresponding attributes selected for this study were based on broader issues surrounding crop and plant-based biofuels. The attributes were identified through a rigorous literature review (Chapter 2). These attributes were narrowed into four key impacts: (1) net emissions, (2) impacts of a local industry, (3) biodiversity, and (4) food price. The understanding of the value of these issues in the context biofuels was unknown. Hence, this study provided essential information not only to the production of biofuels but more importantly, to the policy surrounding biofuels in Australia.

A key aspect of this study is accounting for the marginal values of externalities through individual consumer preferences. This approach is consistent with the literature identified in this section, in particular the studies by Susaeta et al. (2010) and Khachatryan et al. (2011). Also, fuel consumption for passenger vehicles and motorcycles (taken as a proxy for individual consumers) represents the majority of fuel consumed at 58.7% (Australian Bureau of Statistics, 2015b, Table 13). However, it should be noted that a large proportion of fuel consumption in Australia is attributed to business/commercial purposes (41.3%) (Australian Bureau of Statistics, 2015b, Table 13). The justification for focusing on individual consumption is that government representatives (and their accompanying policy decisions) are explicitly voted for by individuals rather than by businesses. Hence, determining the marginal value for the externalities based on individual consumer preference would yield a better representation of the economic values.

The hypothesis for this study was that while the WTP for biofuels have been relatively low, consumers would have a higher WTP for biofuels with more external benefits when faced with biofuel-only options with the same practical attributes. In particular, emissions would be among the highest valued given its prevalence in the literature.

5.3. Methodology

DCEs are widely used to evaluate consumer preferences and establish non-market values in the field of environmental and transport economics. The theoretical underpinnings have been well established in the economics literature. However, the econometric specification often entails more complex processes, particularly in the presence of attribute non-attendance and heterogeneity in consumer choices. Both theoretical underpinnings and econometric specifications to be used in this study will be described further in this section. Subsequently, the survey design and implementation will be detailed. This will then lead into the next section, which will describe the sample data and present the results from the econometric analysis.

5.3.1. Theoretical underpinnings

As previously mentioned, participants in a DCE make choices from a set of alternatives. Their responses are then used to estimate economic values for various attributes that define each alternative. This methodology[38]is centred on the fundamental microeconomic concept of utility maximization with budgetary constraints. Using the Lancastrian approach, where consumer utility is based on the attributes associated with the good, an individual, i, given a set of n alternative choices, will make his/her choice, c, based on a set of attributes (represented by the vector $\boldsymbol{A}$), that maximises his/her utility, u (equation 5.1). The individual

[38] This section is adapted from theoretical underpinnings outlined in Alpizar, Carlsson, and Martinsson (2003), Hensher et al. (2005a), and Train (2009).

is constrained by his/her income, m, and the purchase of a fixed vector of ordinary goods outside of this choice decision, **z** (*i*), and the price of each choice p_n. An assumption is made that the individual is open to a vector of substitute choices but will choose one (and only one) alternative (*ii*), and without a 'no-choice' option (*iii*).

$$\max_c \; u_i[\mathbf{c}(\mathbf{A}); \mathbf{z}] \tag{5.1}$$

$$\begin{aligned}
&s.t.\\
&(i) \quad m = \textstyle\sum_{n=1}^{N} p_n c_n(\mathbf{A}_n) + \mathbf{z}\\
&(ii) \quad c_n * c_o = 0, \; \forall\, n \neq o\\
&(iii) \; c_n > 0
\end{aligned}$$

In this study, a representative individual is assumed to have a fixed income to spend on the given choice, as derived from (*i*), at a respective unit-equivalent price, p_n. The conditional utility function, *V*, then dictates that the individual chooses an alternative *n* based on the function (equation 5.2).

$$\mathrm{V}_i(\mathbf{A}_n,\; p_n) > \mathrm{V}_i(\mathbf{A}_o,\; p_o) \tag{5.2}$$

As with other models that attempt to model human behaviour, SP (and RP) models tend to diverge from actual human behaviour due to the possible non-deterministic nature of the model specification. There are many possible sources of the inconsistencies. One source is the non-inclusion of individual characteristics and attribute preferences that explain the heterogeneous nature of individual utility functions. This is often accounted for through the inclusion of broad demographic characteristics that have been regarded as possible sources for the heterogeneity, and relevant attribute values and levels based on *a priori* assumptions. However, these measures do not account for all potential stochastic components in the specification, including issues from measurement errors. Hence, a Random Utility approach is preferable, with the inclusion of a stochastic disturbance term in addition to deterministic variables such that the representative individual with an aggregate utility function, *V*, chooses alternative n, based on components identified in equation 5.1, a vector of components reflecting demographic characteristics, $\boldsymbol{y}_i$, and the respective stochastic term ε.

$$\mathrm{V}[\mathbf{y}_i,\ \mathbf{A}_n,\ p_n,\ \varepsilon_n] > \mathrm{V}[\mathbf{y}_i,\ \mathbf{A}_o,\ p_o,\ \varepsilon_o],\ \forall\, n \neq o \tag{5.3}$$

5.3.2. General econometric specification

This section will present a generic econometric derivation/specification for the intended modelling. DCE data are estimated using limited dependent variable models. The general specification is based on the nature of the dependent variable i.e. the number of alternative choices for the respondents. Therefore, the individual makes a choice of option n based on the function (equation 5.4), where $V(\ .\ )$ represents the utility function of a discrete choice based on individual characteristics and choice attributes as in (3).

$$P_i\{c_n = 1\} = P_i\{\mathrm{V}_n(\ .\ ) > \mathrm{V}_o(\ .\ ),\ \forall\, n \neq o\} \tag{5.4}$$

These functions are often estimated using multinomial logit (MNL) models based on the probabilities of choosing an option given a set of alternative options and a set of observed choices. Each choice is represented by a limited dependent variable, namely 1 if the option is chosen or zero otherwise. Assume that an individual is given a set of alternatives, S_f, which consists of N_f alternatives such that $S_f = \{\boldsymbol{A}_{1f},\ \boldsymbol{A}_{2f},\ \ldots,\ \boldsymbol{A}_{Nf}\}$ and (as in equation 5.1) $\boldsymbol{A}$ is a vector of attributes for each alternative. The choice probability function 5.4 is then transformed into 5.5 based on the assumption that the error term is additive in the utility function.

$$\begin{aligned}P_i\{c_n = 1|S_f\} &= P_i\{\mathrm{V}_n(\boldsymbol{y}_i, \mathbf{A}_{nf}, p_n, \varepsilon_n) > \mathrm{V}_o(\boldsymbol{y}_i, \mathbf{A}_{of}, p_o, \varepsilon_o);\ \forall\, n \in S_f\} \\ &= P_i\{\mathrm{V}_n(\ .\ ) + \varepsilon_n > \mathrm{V}_o(\ .\ ) + \varepsilon_o;\ \forall\, n \in S_f\} \\ &= P_i\{\mathrm{V}_n(\ .\ ) + \varepsilon_n - \mathrm{V}_o(\ .\ ) > \varepsilon_o;\ \forall\, n \in S_f\}\end{aligned} \tag{5.5}$$

The generic choice probability can be shown using the joint cumulative density function (CDF) of the error term:

$$P(c_n = 1|S_f) = CDF_{\varepsilon|S_f}(\mathrm{V}_n + \varepsilon_n - \mathrm{V}_1\ ,\ \mathrm{V}_n + \varepsilon_n - \mathrm{V}_2\ ,\ \ldots\ ,\ \mathrm{V}_n + \varepsilon_n - \mathrm{V}_N) \tag{5.6}$$

which is expressed as a product of the individual CDFs for all $o \neq n$.

$$P(c_n = 1|\varepsilon_n) = \prod_{o \neq n} e^{-e^{-[\mathrm{V}_n(\,.\,)+\varepsilon_n-\mathrm{V}_o(\,.\,)]}} \tag{5.7}$$

The MNL assumes that each error term is independently and identically distributed (IID) extreme value distributed (Gumbel/Type-I distribution) (McFadden, 1974) where $CDF(\varepsilon_n) = e\,[-e\,(-\,\varepsilon_n)]$.

Maintaining the assumption that the error component is unknown, the choice probability is therefore the integral of function 5.7 over all values of ε_n weighted by its density (Train, 2009).

$$P(c_n = 1) = \int (\prod_{o \neq n} e^{-e^{-[\mathrm{V}_n(\,.\,)+\varepsilon_n-\mathrm{V}_o(\,.\,)]}}) e^{-\varepsilon_n} e^{-e^{\varepsilon_n}} d\varepsilon_n \tag{5.8}$$

This solution collapses to the expression,

$$P_i(c_n = 1) = \frac{e^{V_i n}}{\sum_{N=1}^{N_f} e^{V_i N}} \tag{5.9}$$

$$= \frac{e^{\beta \mathbf{x}_{in}}}{\sum_{N=1}^{N_f} e^{\beta \mathbf{x}_{iN}}}$$

where the utility functions are linear in parameters of observable attributes and demographic characteristics, $\boldsymbol{x}_{in}$ and their respective coefficients, $\boldsymbol{\beta}$ (both represented as vectors).

Using the dummy for choice $c_n = 1$ for every option in S_f, the likelihood function for each individual is defined as,

$$\mathcal{L}_i = \prod_{n=1}^{N_f} P_i^{c_n} \tag{5.10}$$

and for the entire sample,

$$\mathcal{L} = \prod_{i=1}^{I} \prod_{n=1}^{N_f} P_i^{c_n} \tag{5.11}$$

The marginal willingness to pay of an attribute, a_n, is estimated from the coefficients of the MNL regression according to the function

$$MWTP_{a_n} = -\frac{\beta_{a_n}}{\beta_{p_n}} \quad (5.12)$$

where the numerator is the coefficient of the attribute of interest and the denominator is the coefficient of the price/cost of the alternative, *n*. The negative sign is necessary given the assumption that the cost coefficient will be negative (Hensher et al., 2005a).

5.3.3. Model comparisons and selection

As with any econometric analysis, selecting the best estimation model requires attention to various indicators of model fit. The coefficient of determination, or more commonly the R^2 statistic, is commonly used as an indicator of model fit in linear regressions (Greene, 2012). However, in maximum likelihood estimations – the estimation procedure used for MNL – R^2 statistics are not calculated (as they are based on residual sums of squares that form part of the regression model estimation). Instead, a common alternative measure in maximum likelihood estimation is the pseudo-R^2 estimate, although this is not directly comparable to the R^2 from linear regression. The latter provides a ratio of estimated residuals over the total, thereby illustrating how well the model fits or explains variation in the data. Conversely, the former uses the log-likelihood (LL) functions of the non-linear estimation to calculate the pseudo-R^2. Hensher et al. (2005a) add that while there is a similarity between this pseudo-R^2 and R^2, the interpretation of each differs. They suggest pseudo-R^2 between 0.3 to 0.4 to be ideal and loosely comparable to an R^2 of 0.6 to 0.8 for a linear model (Hensher et al., 2005a, pp. 338-339). As with the adjusted R^2, the adjusted pseudo-R^2 allows the effects of expanding the number of parameters in the model (Greene, 2012).

Like the adjusted pseudo-R^2 (which will be referred to the adjusted-R^2 henceforth), the Akaike Information Criterion (AIC) accounts for both goodness-of-fit and expanded model parameters. The AIC is often more preferred as it can ensure a better model performance indicator with increases in the sample size (Greene, 2012). The AIC is given as

$$AIC = \frac{-2 \ln L + 2p}{N} \tag{5.13}$$

where L is the likelihood function as defined in (5.11), p is the number of parameters and N is the sample size. The AIC is a relative rather than absolute measure, used for comparing different model variants with a common dependent variable. Generally, a lower AIC indicates a better model performance.

5.3.3.1. Heterogeneity

While DCE aims to capture as much information on how individual makes choices, these tasks are often determined by various factors. Some of these factors, known as heterogeneity, can be captured through further information collected and relatively simple econometric techniques (i.e. censoring responses, panelling data, partitioning/split-sampling). There are also sources of heterogeneity that are not captured through survey design or socio-demographic/psychographic elements. Such unobserved heterogeneity requires more complex processes and estimation. These include using Random Parameters Logit (RPL) models and Latent Class Modelling (LCM). These methods can also be used to overcome issues with assumptions of Independence of Irrelevant Alternatives and Attribute Non-Attendance, which will be described later.

Random Parameters Logit (RPL) models

RPL[39] estimation can address unobserved heterogeneity by relaxing the constraints of the error component in the MNL estimation. It assumes that individual preferences vary across respondents and the error term can take on alternative distribution forms like normal, lognormal, uniform, or triangular, with normal being the most common (Hensher et al., 2005a). The more constrained triangular distribution has been suggested for heterogeneous

[39] Also referred to as mixed logit (MXL), mixed multinomial logit, or hybrid logit models (Hensher et al., 2005a, p. 605).

cost/price parameters, due to greater behavioural realism and a negative parameter (Beharry-Borg & Scarpa, 2010; Hensher & Greene, 2003).

As the individual respondents in choice experiments generally provide choices for several sets of comparisons, the data are effectively panel data rather than a set of independent observations. Accounting for the panel nature of the data is important for RPL, as the assumption is that heterogeneity exists between individuals, not individual choices.

Latent class models (LCM)

An alternative to estimating unobserved heterogeneous preferences is to utilise LCM. This approach assigns respondents to classes based on endogenously determined similarity in choices; estimating the probability to membership and respective parameters for each of the classes (Scarpa & Thiene, 2005). The number of classes is determined by the analyst and decided through the lowest AIC (Beharry-Borg & Scarpa, 2010; Bhat, 1996). The probability of individual membership to specific classes can then be used to illustrate socio-demographic or psychographic characteristics that determine membership in a particular class via separate probit or tobit regressions. This could better identify the socio-demographic or psychographic characteristics that identify individuals to a specific class with related attribute preferences.

5.3.3.2. Independence of Irrelevant Alternatives (IIA)

A key assumption from an MNL estimation of DCE data is that the probability of choosing between two alternatives is independent of other alternatives in the choice set (Luce, 1959) or "equally similar or dissimilar" (Hensher et al., 2005a, p. 249) known as the Independence of Irrelevant Alternatives (IIA). This assumption has implications on the IID assumption outlined previously, as violation of the IIA assumption would suggest that information captured in the error component would be not similar between pairs of choice alternatives i.e. violating the IID assumption (Hensher et al., 2005a). The validity of the IIA assumption in analysis can be tested through a Hausman-McFadden (1984) test. In the test, two separate models are estimated with one being an unrestricted variant with all alternatives and another restricting each of the available alternatives. A hypothesis test is conducted to test if the assumption can be rejected (p-value being less than α of 0.05). If rejected, models that are more complex and relax the IIA assumption can then be estimated, such as the Nested Logit or Random Parameters Logit (RPL) models (Hensher et al., 2005a). The use of RPL or mixed logit models to avoid restrictions from the IIA has been used successfully in the context of consumer choice for alternative vehicles (Brownstone & Train, 1998) and was employed for this study.

5.3.3.3. Attribute non-attendance

In DCEs, the respondents are assumed to make trade-offs as they consider all attributes associated with the different choices. However, the literature has identified that respondents may choose to make their trade-offs based on only a subset of the attributes, ignoring one or more (Hole, Kolstad, & Gyrd-Hansen, 2013). Several studies have shown that significant proportions of respondents do ignore at least one attribute in DCEs (Carlsson, Kataria, & Lampi, 2010; Hensher, 2006; Hensher, Rose, & Greene, 2005b). This behaviour, known as attribute non-attendance (ANA) is caused either by respondents ignoring particular attribute(s) (discontinuous preferences) (D. Campbell, Hutchinson, & Scarpa, 2008; Lockwood, 1996; McIntosh & Ryan, 2002), making choices based on only a single attribute (lexicographic preferences) (Sælensminde, 2002), or making choices with inconsistent trade-offs i.e. at random. The last of these reasons could relate to the cognitive burden that respondents might encounter (which was described previously). This can result in biased estimates due to incorrect interpretations of marginal rates of substitution between ignored attributes (Hensher & Rose, 2009; Kragt, 2013). In addressing the issue of ANA, the literature has suggested it reduces likelihood of bias (Hensher & Rose, 2009) and improves model fit (Hess & Hensher, 2010).

There are generally three ways to detect and account for ANA. Firstly, it can be done through examination for inconsistency in choices, particularly for discontinuous or lexicographic preferences (Sælensminde, 2002). However, the effort costs associated had led to the next two methods being more commonly employed in the literature addressing ANA.

The second method involves collecting information from respondents through supplementary questions i.e. if they had consistently ignored any attributes in their decision-making. As respondent-reported data is collected, this method captures 'stated non-attendance' (SNA). The supplementary or follow-up questions can be asked after each choice task (Hensher, 2006; Puckett & Hensher, 2008, 2009; Scarpa, Thiene, & Hensher, 2010) or at the end of the entire experiment, known as serial non-attendance. The latter is less costly for respondents and analysts, and works with the assumption that individuals systematically ignore the same attribute(s) across the choice tasks (Kragt, 2013). This information is then used to restrict the response of an individual to zero if SNA was reported for a respective attribute. In addition to the increased time (and monetary) cost of the survey, SNA methods also come with the major issue of respondents being unable to accurately identify or potentially misreporting their non-attendance to attributes (Balcombe, Burton, & Rigby, 2011; Kragt, 2013). Hence, constraining or removing responses with SNA methods would result in biased estimates and loss of relevant preference information.

Finally, ANA can be investigated through more complex econometric methods, capturing 'inferred non-attendance' (INA). Some examples include using random parameters logit

(RPL) estimation (Balcombe et al., 2011; Hess & Hensher, 2010), discrete mixture logit models, and most commonly, utilising latent class models (LCM) (D. Campbell, Aravena, & Hutchinson, 2011; D. Campbell et al., 2008; Hensher, Rose, & Greene, 2012; Scarpa, Gilbride, Campbell, & Hensher, 2009) where class attendance is determined by constrained attribute coefficients to zero. In this study, the LCM approach was utilised by constraining the attributes to zero to specify the classes for ANA for single attributes, full ANA to all attributes, and as a comparison, full attendance to all attributes. The individual probability of class attendance was then utilised to determine individual characteristics (socio-demographic and psychographic) that could determine ANA behaviour i.e. what characteristics could determine the likelihood of non-attendance to specific attributes.

5.3.4. Survey design

The DCE was aimed at deriving the consumer preference for biofuels in Australia. Hence, two key design steps of the survey were noted: (1) the intended sample had to be representative of the Australian population who were likely transport fuel consumers and (2) the DCE would involve different biofuel alternatives rather than choices with fossil fuels (petrol/diesel). For the former, respondents had to have a driver's license. For the latter, it was noted that biofuels do not realistically represent perfect substitutes (i.e. a drop-in fuel) at 100%. Therefore, the scenario was presented that respondents had to make choices under the assumption that the respective biofuels would be blended with petrol or diesel similar to blend concentrations currently available in the market (e.g. E10[40], B5[41]). This would also justify the assumption that all biofuel options would have similar performance and mileage, given marginal impacts of low proportions of biofuels in blends (Xue et al., 2011).

[40] A blended fuel consisting of 10% ethanol biofuel and 90% petrol.
[41] A blended fuel consisting of 5% biodiesel and 95% diesel from crude oil.

The survey questionnaire was divided into the following sections: (1) a section of screening questions that ensured the sample was representative of the intended population and met with design requirements, (2) an introductory section covering the driving and fuel preferences, and perceptions on biofuels, (3) the choice experiment and questions on how choices were made, and (4) a section on socio-demographic characteristics of the respondents.

5.3.4.1. Screening questions

As previously mentioned, the intended sample was to be representative of the Australian population, consist of likely consumers of transport fuels, and be able to meet consent requirements for the online survey. Hence, five screening questions were asked before proceeding with the remainder of the survey. Firstly, respondents were asked to which age bracket they belonged, out of seven categories. Those in the first category (under 18) were excluded from the survey[42]. This was because part of the ethical requirements for the survey was that respondents under 18 years would need parental consent, which would be difficult to ensure compliance in online surveys. The distribution across the remaining age groups was maintained with the census data on the same age brackets; if a particular age group was fully represented based on the intended sample size and population statistics, no further respondents from that age group were accepted for the survey. Similarly, two further questions on gender and state of residence were used to ensure the sample was an adequate representation of the Australian population. Next, self-reported postcodes of respondents were collected. This question was not used to stratify the sample but merely as a follow up question to that of the state of residence. Finally, respondents were asked if they had a driving licence; if they did not, there were excluded from the survey.

[42] The breakdown of the other six groups will be shown later in Table 5.2.

5.3.4.2. Driving and fuel preferences

The next section after the screening questions included questions on driving and fuel preferences. These included questions to gauge experience (e.g. number of years with licence, number of hours driving per week, most commonly used vehicle), expenditure (e.g. how many vehicles owned, weekly expenditure on fuel), fuel preferences (e.g. most regular fuel used, use of premium fuels), and perceptions of biofuels (e.g. prior use of biofuels, familiarity of biofuels, interest in biofuels). A number of follow-up questions on fuel use and perceptions were included to find reasons for responses (e.g. why or why not a biofuel user, why or why not a premium fuel user); these included multi-choice and open-ended options. The specific questions will be outlined in the following section (section 5.4) where the results will be discussed.

5.3.4.3. Choice experiment

According to Hensher et al. (2005a), the attributes and respective levels are essential to maintaining the research interests of the study. It is important to ensure that the relevant attributes involved in real choices are included. These attributes should be defined as objectively as possible to avoid issues of incommensurability between respondents. The number of attributes and levels should be sufficient to allow sufficient variation to understand choice decisions but limited to avoid over-complexity (Adamowicz et al., 1998a). Additionally, sufficient precautions are to be taken to ensure that other important attributes that may be relevant to the respondent's choice, but are not included, are addressed through the experiment design to avoid bias in the estimates.

In this study, the main aim was to derive the economic values for the various attributes associated with different biofuel alternatives, comparing the benefits of newer alternatives (e.g. microalgae) to the conventional (e.g. corn, sugarcane molasses). Hence, the premise of this choice experiment, as detailed in a pre-experiment briefing to respondents, was based on a hypothetical but realistic scenario of a mandated biofuel policy in Australia where a biofuel-blend would replace regular petrol/diesel. Respondents would choose between three types of biofuels that would be sold in a fuel blend (e.g. E85 15% ethanol, 85% petrol or B5 5% biodiesel, 95% diesel) through a policy forcing increased biofuel consumption. All practical aspects of the three biofuel alternatives would be the same, with the only differences being defined by the attributes and respective levels. The three alternatives were unlabelled (defined as Biofuels A, B, and C) to avoid issues of leading or forcing respondents. Respondents were told that their respective state governments were choosing a status quo, Biofuel C, and they were given the opportunity to suggest the biofuel they would most prefer between the three alternatives.

Attribute selection

The selection of the attributes for this study were based on a review of both choice experiment literature on biofuels (Khachatryan et al., 2011; Susaeta et al., 2010) and an extensive review of the benefits and limitations of specific biofuel feedstocks that were relevant to this study (Chapter 2). The non-price attributes were narrowed into four key impacts: emissions, trade (source), food price, and biodiversity. These are briefly described below.

1. Emissions

While biofuels can have lower carbon dioxide emissions than petrol/diesel, the cultivation of the crop/plant biomass has also been found to absorb carbon dioxide from the atmosphere. The amount of carbon dioxide absorbed during cultivation varies according to the type of crop/plants but can also be cancelled out during the processing into biofuels.

2. Source

Studies have suggested that it may not be economical to produce certain biofuels in Australia and as such, part of the biofuel supply will depend on foreign imports (20-50%). This is dependent on the crop/plant type, production technologies, and the availability of sufficient resources to produce them.

3. Food price

Increasing production of certain crop/plant-based biofuels can result in competition for crops and other resources (e.g. water, land), resulting in higher food prices. Others can potentially reduce food prices by reducing such competition.

4. Biodiversity

Increasing production of some biofuels can result in clearing of forests and/or expansion of agricultural land, which has been found to affect the richness in diversity of bird, animal, and plant species native to specific farmland and forests. These impacts on biodiversity are dependent on the type of crop/plants, with some potentially increasing biodiversity by reducing the need for such land clearing.

5. Price

Biofuels are generally more expensive than petrol/diesel but some biofuels are cheaper than others based on cultivation and processing technologies.

Level selection

In addition to the selection of attributes, the selection of levels that defined each attribute was essential in determining the efficiency of survey design in describing the consumer choice. This involved selecting an appropriate number of levels for each attribute, having sufficient variation between each level, and the choice of quantitative or qualitative descriptions for each attribute. There were clear trade-offs between choosing more levels over fewer. More levels would allow for more detailed attribute description and robust analysis of the respondent's utilities but this increases complexity of the choice experiment. The same applies to the variation between each level. The choice of description raised trade-offs of simplicity (with qualitative descriptions) versus reducing incommensurability (with quantitative levels).

For this choice experiment, it was decided that five levels for each attribute would be sufficient, with the source attribute (local or imported) being the only dummy (Table 5.1). Also, a quantitative description of each attribute level (except source) was preferred, with care taken in the description of levels to reduce complexity. Consideration was given in framing the attributes as absolute levels or using percentage deviations from a reference point. Kragt and Bennett (2012) investigated the difference between framing attributes as absolute terms and as relative proportions, and found no significant difference in SP estimates. Hence, relative percentages was chosen under the assumption this would avoid inconsistencies in valuation between respondents across socio-economic backgrounds, and different income groups.

Table 5.1: Attributes and levels.

Attribute	Levels
EMISSIONS	50% reduction, 25% reduction, No change, 25% more, 50% more
SOURCE	Local, Imported
FOOD PRICE	20% cheaper, 10% cheaper, No change, 10% more expensive, 20% more expensive
BIODIVERSITY	50% loss, 25% loss, No change, 25% gain, 50% gain
PRICE	20% cheaper, 10% cheaper, No change, 10% more expensive, 20% more expensive

In this experiment, it was assumed that respondents would exhibit symmetric preferences for gains and losses for each attribute. A study by Hess, Rose, and Hensher (2008) suggested this this might not be the case but as the first study in this context, this was not investigated for this study. There is the potential to investigate the presence of such asymmetric preference in future study, either using the same sample or in another related study.

Finally, the variation between each level was decided through the survey design process using the software NGene 1.1.1 (Choice Metrics Pty Ltd, 2012), where the combination of base parameters for each utility function and the levels would be manipulated to produce the most efficient choice experiment design, measured by D-error (Rose & Bliemer, 2013) with a minimum sample requirement of 550 responses. This was preferred over the alternative of a full factorial design where each respondent completes choice tasks for each possible option (Hensher et al., 2005a), which would total 1250 (5x2x5x5x5) combinations. The status quo option for each choice scenario was a 'no change' for each attribute and 'imported' for the source attribute. A total of 32 choice sets were generated, which were grouped into four blocks of eight choice sets. A sample choice scenario is shown in Figure 5.1.

Figure 5.1: Example of choice scenario.

Scenario 1:

Consider the following three biofuel options. Assuming these are the only options available to you, which one would you choose?

Attribute		Biofuel A	Biofuel B	Biofuel C
Emissions		25% Reduction	25% More	No change
Source		Imported	Local	Imported
Food price		10% Cheaper	No change	No change
Biodiversity		25% Loss	25% Gain	No change
Fuel price		10% More expensive	10% Cheaper	No change

The choice experiment section was preceded with a simplified but detailed description of the context and tasks of the choice experiment, which the respondent could refer to at any time when completing the choice tasks[43]. Each respondent was allocated a block of eight choice tasks to complete, which was randomly but uniformly selected from the four blocks. The choice sets within each block were also presented randomly to each respondent.

After the choice experiments were completed, respondents were presented with a series of debriefing questions that would elicit how the choices were made. This included asking the respondents to rank the importance of each attribute in a Likert-5 scale, and how many and which attributes were ignored when making their choices. These questions would then be used as a method in assessing the serial ANA. This method was preferred over a similar question after each choice task, which was assumed to be excessively arduous and time-consuming for the respondent.

5.3.4.4. Socio-demographic characteristics

The final section of the survey involved collecting various indicators of respondents' socio-demographic characteristics. This included household size, association with fuel and farming industries, educational qualifications, and income. Also, information was collected to identify the environmentalism and political beliefs of the respondent; the former through a proxy question on membership to any environmental groups and the latter through a self-reported ranking on a 10-point scale of conservative beliefs.

5.3.5. Survey implementation

Ethical clearance for this survey was approved by Queensland University of Technology's University Human Ethics Research Committee (approval number: 1500000634). Participants for the survey were collected through a random sampling approach of the Australian general

[43] These descriptions were the same as those previously described in the '*Attribute selection*' sub-section.

public based on age, gender, and geographical location through panels from an Australian survey company, The Online Research Unit (ORU). A pilot launch was run from the 25th August 2015 to the 26th August 2015 where a sample of 105 responses was collected. These choice experiment responses for the pilot were modelled using an MNL model with the dependent variable being a dummy of the choice from the three alternatives for each choice scenario and the independent variables being the respective levels for each attribute. The resulting estimates were used to redesign the choice experiment on NGene (Choice Metrics Pty Ltd, 2012) using the same attributes and levels. The new experiment design was found to be more efficient (lower D-Error). The redesigned survey was re-launched on 2nd September 2015 and a combined sample (including pilot responses) of 556 was collected by 8th September 2015. A version of this online survey is presented in Appendix E.

5.4. Data description and analysis

In this section, the data collected from the survey described in the previous chapter will be described and analysed. The first section details various descriptive statistics of the sample, including various socio-demographic indicators, driving and fuel expenditure of the respondents, and the use and perception of biofuels. Subsequently, the results from the choice modelling will be presented. This will include models capturing various sources of heterogeneity, particularly with attendance to attributes. The results will be used to address the question on consumer preferences for biofuels and how it can influence the potential market for alternative biofuels and policy, which will be put forth in the discussion in the next section.

5.4.1. Descriptive statistics of sample

The distribution of respondents by age groups with that from the population is compared in Table 5.2. A chi-squared goodness of fit test found that there is insufficient statistical evidence to suggest the distribution of respondents across the defined age groups was significantly (at a 5% level) different from the population distribution across the same age groups. The difference between the population and sample statistics for the oldest age group (over 65) was the largest at 3.1%. However, given that the survey was conducted online, a reasonable assumption would be that the average age of respondents over 65 would be lower in the sample than from the population census.

Table 5.2: Age distributions for population and survey sample.

Age groups	Population*	Survey sample
18-24	12.4%	14.2%
25-34	19.0%	17.4%
35-44	17.7%	19.2%
45-54	17.0%	16.2%
55-65	16.1%	18.3%
Over 65	17.7%	14.6%

*Population statistics adapted from Australian Bureau of Statistics (2015a, Table 59)

In comparing the origin of respondents with the latest population statistics, the sample represented a decent representation of the population of Australia in terms of distribution across states (Table 5.3). A chi-squared goodness of fit test found that there was insufficient statistical evidence to suggest that the distribution of survey respondents was significantly (at a 5% level) different from the population distribution. A large majority of the sample (73.7%) had stated that they were born in Australia.

Table 5.3: Distribution across states for population and survey sample.

State	Population†	Survey sample
Australian Capital Territory (ACT)	1.6%	1.8%
New South Wales (NSW)	32.0%	32.9%
Northern Territory (NT)	1.0%	1.1%
Queensland (QLD)	20.1%	19.4%
South Australia (SA)	7.2%	7.4%
Tasmania (TAS)	2.2%	2.2%
Victoria (VIC)	24.9%	26.8%
Western Australia (WA)	10.9%	8.5%

†Population statistics adapted from Australian Bureau of Statistics (2015a, Table 8)

Residential postcodes were also collected from respondents to gauge the distribution of respondents across metropolitan areas. The distribution of respondents from metropolitan areas of the country by state, based on postal classifications[44], is shown in Table 5.4. A majority of respondents (62.6%) across the entire sample were from metropolitan areas.

Table 5.4: Percentage of respondents from metropolitan areas.

State	% of respondents
ACT	30.0%
NSW	55.7%
NT	83.3%
QLD	52.8%
SA	85.4%
TAS	41.7%
VIC	65.8%
WA	91.5%

A comparison between the population statistics and survey sample in terms of gender is given in Table 5.5. This was the only demographic where the survey sample was found to vary significantly (at a 5% level) from the population statistics. This could possibly be due to the disparity between the population and survey sample in the oldest age group (over 65), with

[44] http://www.impactlists.com.au/ImpactLists/media/list-tools/Useful-Postcode-Ranges.pdf

the population statistics showing a higher proportion of females in only this age bracket by over 2% as compared to the other age brackets where men had a higher proportion by less than 1% for all groups.

Table 5.5: Gender distribution for population and sample survey.

Gender	Population‡	Survey sample
Female	50.7%	46.0%
Male	49.3%	54.0%

‡Population statistics adapted from Australian Bureau of Statistics (2015a, Table 59)

The educational demographics of the sample and population is compared in Table 5.6. The sample consisted of generally higher educated respondents relative to the population. Almost 30% of the population reported that they had less than a Year 12 high school certificate but this group represented just over 11% of the sample. Conversely, tertiary qualifications were represented by almost 75% of the sample, with 14.6% having post-graduate qualifications.

Table 5.6: Distribution of educational attainment for population and survey sample.

Education level	Population§	Survey sample
Below high school certificate (below year 12)	28.80%	11.2%
High school certificate (Year 12)	16.60%	16.9%
Diploma/Tertiary Certificate	23.30%	28.6%
Bachelor's degree (BSc, BA)	13.50%	28.8%
Post-graduate (MSc, PhD)	5.3%	14.6%

§Population statistics adapted from Australian Bureau of Statistics (2011b).

Respondents were asked about their areas of study and if they already had or are pursuing a university degree (n=272) (Table 5.7). Science-based courses had the greatest representation with 25.7%.

Table 5.7: Distribution across educational fields for university graduates and students.

Educational field	Survey sample
Science/engineering (including medical studies)	25.7%
Accountancy/Finance	13.6%
Social sciences	13.6%
Business studies	11.4%
Health	9.6%
Education	7.0%
Economics	4.8%
Law	3.7%
IT & Multimedia	3.3%
Arts	2.6%
Architecture & construction	1.1%
Philosophy	1.1%
Languages	0.7%
Librarian	0.4%
Religious studies	0.4%
Project management	0.4%
None specified	0.7%

The sample distribution across personal pre-tax incomes is shown in Table 5.8. The sample was relatively similar in distribution across the first three income brackets (outside of those reporting nil income). The distribution suggested majority of respondents were earning under $65,000 per annum.

Table 5.8: Distribution across income ranges.

Income bracket (group[I])	Survey sample
Nil income (1)	7.91%
$1 - $20,799 (2)	19.60%
$20,800 - $41,599 (3)	21.76%
$41,600 - $64,999 (4)	18.88%
$65,000-$77,999 (5)	8.27%
$78,000-$103,999 (6)	11.87%
$104,000-$129,999 (7)	5.22%
$130,000-$155,999 (8)	2.34%
$156,000-$181,999 (9)	1.98%
$182,000-$207,999 (10)	0.54%
$208,000-$259,999 (11)	1.08%
$260,000 or more (12)	0.54%

[I]Income group refers to group number defined in survey and used further in analysis.

As the income ranges were different between the survey and population census, both ranges were modified for comparison (Table 5.9). Non-respondents and incompletes were removed from the census data. A chi-squared goodness of fit test suggests sufficient evidence (at a 5% level) to reject the hypothesis that the distribution of the survey sample across incomes was different from the population census data.

Table 5.9: Income distribution of population and survey sample.

Income bracket	Population**	Survey sample
Nil income	8.27%	7.91%
$1 - $20,799	30.20%	19.60%
$20,800 - $41,599	23.95%	21.76%
$41,600 - $64,999	17.68%	18.88%
$65,000-$77,999	6.04%	8.27%
$78,000-$103,999	7.05%	11.87%
$104,000 or more)	6.81%	11.69%

**Population statistics adapted from Australian Bureau of Statistics (2011a).

In terms of family sizes, respondents were asked about the size of their household and the number of dependent children they had. Majority of the respondents (71.8%) were part of smaller households of three or under (Figure 5.2), and a majority (65.6%) also stated they had no dependent children (Figure 5.3).

Figure 5.2: Distribution across household sizes.

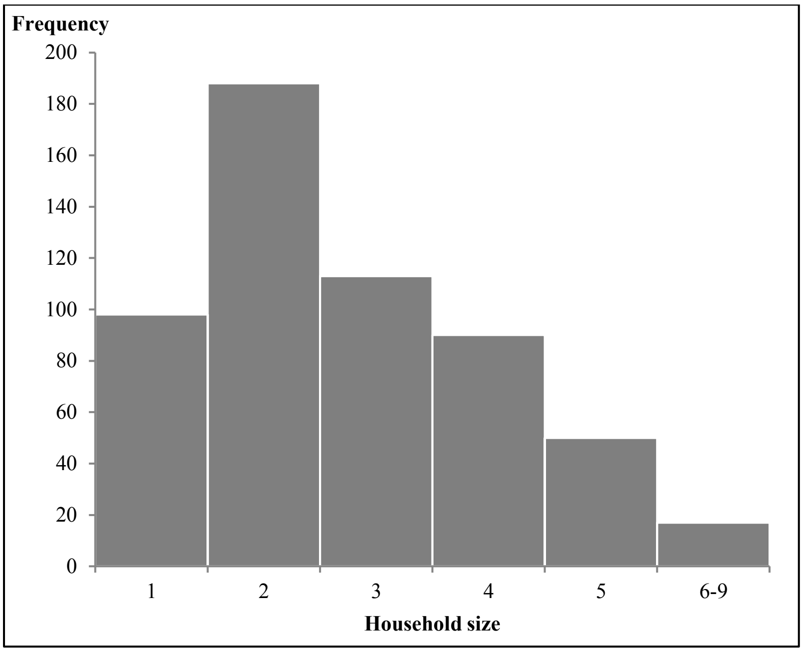
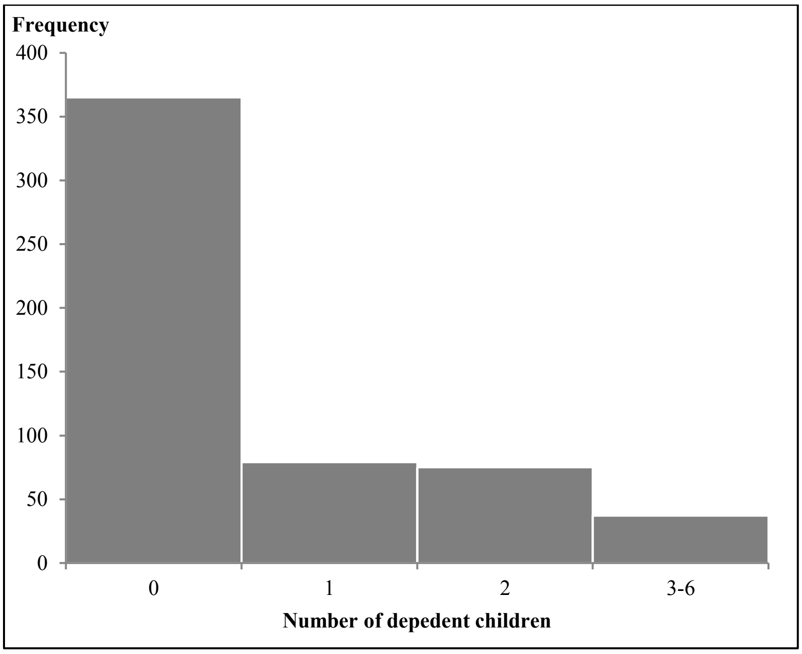
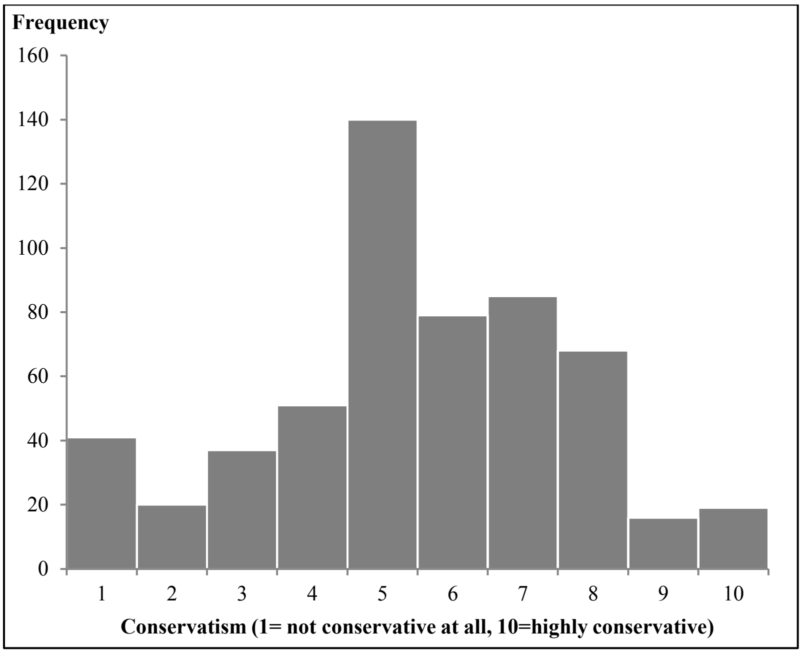


Figure 5.3: Distribution across numbers of dependent children.



Finally, respondents were asked about where they would rank their policy and political support on a 10-point scale of conservatism (Figure 5.4). The majority ranked their own beliefs to be close to the mid-point of the scale of 5, with a greater proportion being more conservative (6 or higher).

Figure 5.4: Distribution across reported levels of conservatism.



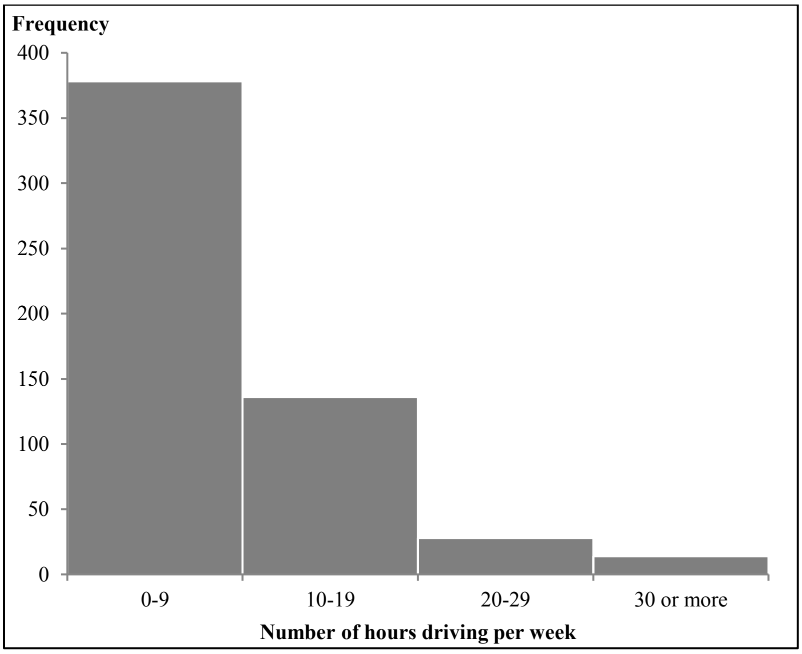
5.4.2. Driving experience and vehicle ownership

Respondents were queried on their driving and fuel preferences through various multi-choice and open-ended questions. To gauge their experience with driving and fuel purchases, they were firstly asked the number of years they had their driving licence (distribution shown in Figure 5.5). The mean driving experience was just over 25 years (25.39) with a standard deviation of 17.13.

Figure 5.5: Distribution across number of years with driving licence.

The distribution of the number of hours the respondents reportedly drove per week on average is shown in Figure 5.6. The majority of respondents (67.9%) drove under 10 hours a week with an average of 7.56 hours per week across the sample.

Figure 5.6: Distribution across number of hours driven per week.



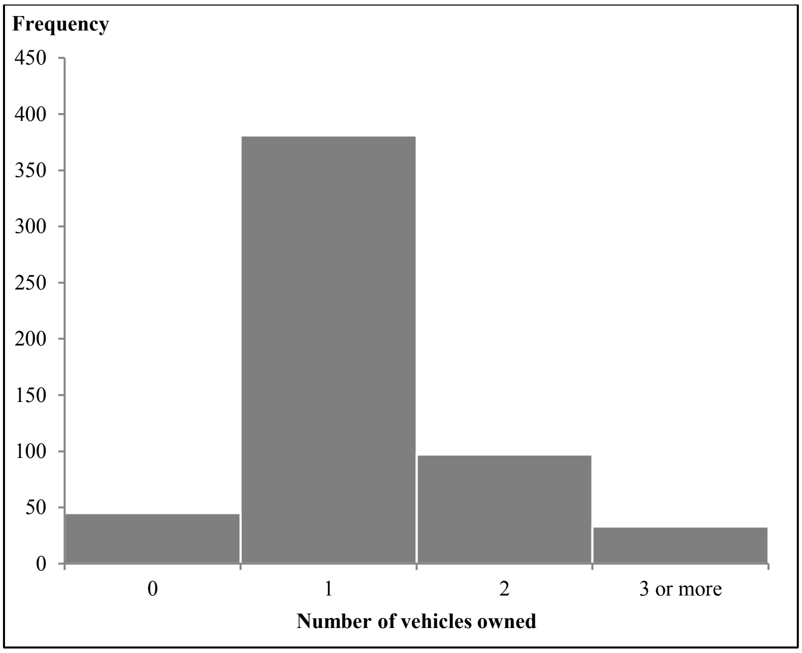
When asked what vehicle did they use the most for personal driving (including rented vehicles but excluding vehicles used for work), a majority drove mid-sized cars (e.g. sedan, hatchback) and just over a quarter (26.4%) drove cars with larger capacities (i.e. SUV, 4WD, minivan/station wagon).

Table 5.10: Distribution across primary vehicle types.

Vehicle type	Examples stated on survey	Percentage
Mid-sized cars	Sedan, Hatchback	56.5%
Large cars	SUV, 4WD, Station wagon, Minivan	26.4%
Small cars	Compact cars (2-seater)	7.7%
Sports cars		2.3%
Utility Vehicle (UTE)		4.3%
Motorcycle		0.5%
Moped/Scooter		0.4%
Bus/van		0.4%
No vehicle		1.4%

Finally, in comparing vehicle ownership, a majority of the respondents were found to have one vehicle (68.5%), with 17.4% having two vehicles, and 5.9% having three or more vehicles (Figure 5.7).

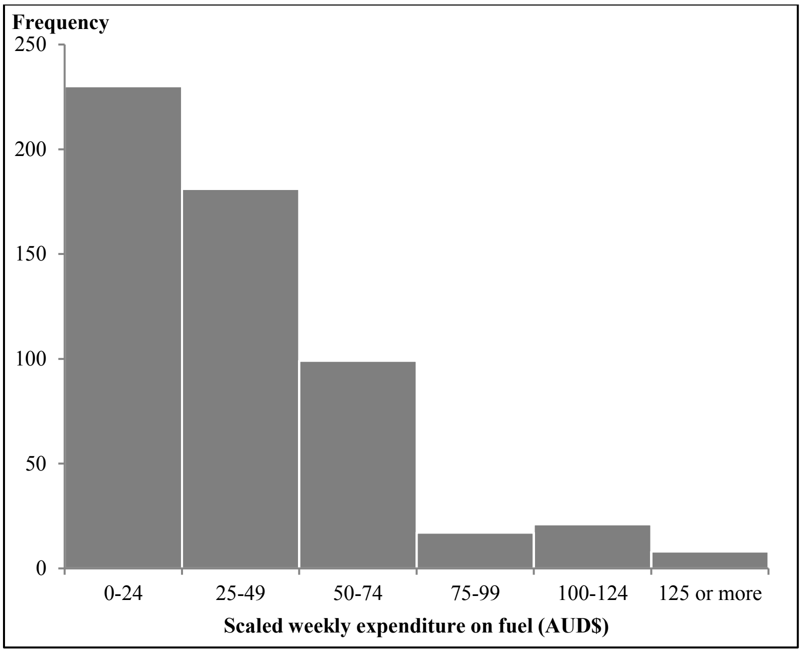
Figure 5.7: Distribution across number of vehicles owned.



5.4.3. Current fuel usage and perceptions

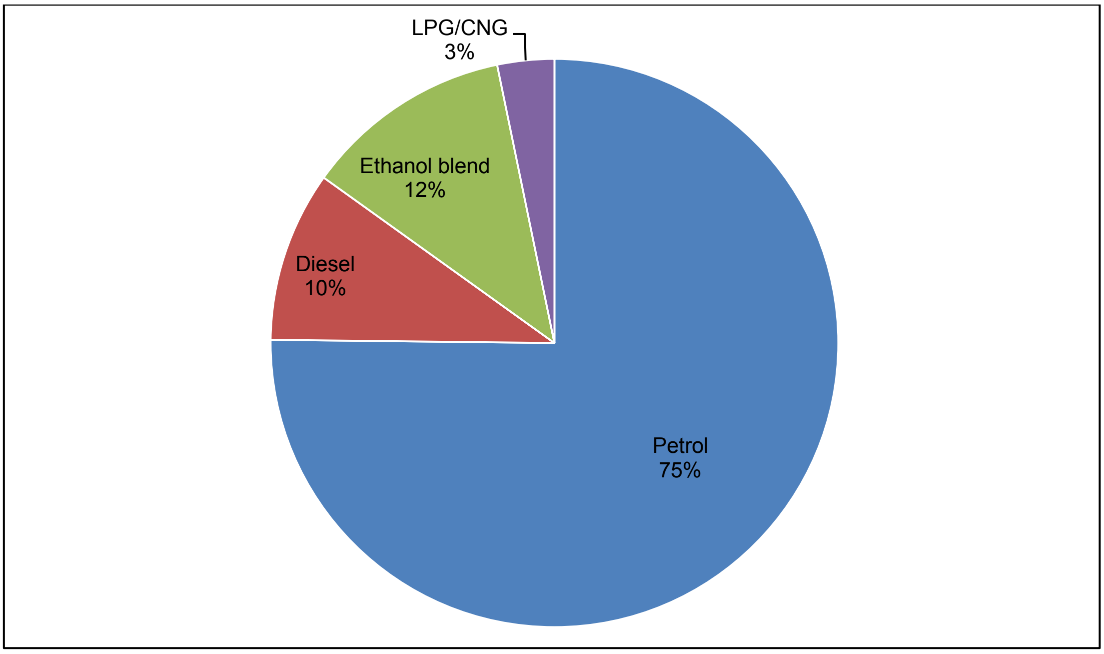
Respondents were asked, in an open-ended question, how much they spend on fuel each week (on average). An assumption to consider was that a proportion of the weekly expenditure could be paid by another party (e.g. younger respondents whose parents contribute to their fuel expenditure, or older and retired respondents whose adult children do the same). As such, respondents were also asked what percentage of the expenditure they paid themselves (across five levels 0% to 100%). This was used to scale the weekly expenditure accordingly. There were relatively few respondents that spent over \$75 a week on fuel, with the mean expenditure being \$34.68 per week (Figure 5.8).

Figure 5.8: Distribution across scaled weekly expenditure on fuel.



In terms of fuel choice (Figure 5.9), no respondents reported being regular users of biodiesel blends or electric vehicles. Expectedly, a large majority were petrol users, with ethanol blend users constituting 12% of the sample. This distribution of fuel usage is different from that reported in national statistics (see Figure 6.1), as this survey focused on individual consumption, excluding business/commercial consumption.

Figure 5.9: Distribution across most regular fuel choice.



However, when asked in a separate question if they used biofuels (and blends) regularly, 17% (n=92) responded affirmatively, with five suggesting the use of biodiesels. These respondents were then asked why they choose to use biofuels, the results of which are shown in Table 5.11. Based on the suggested multi-choice responses, the majority of biofuel users do so for environmental benefits and they also perceived that biofuels were cheaper. The other reasons suggested in an open-ended option for this question were that the respondent wanted to support alternative options and another was restricted to biofuel blends at their local petrol station.

Table 5.11: Reasons for choosing biofuels.

Reason	% responses
Environmental benefits	57.6%
Bought specific vehicle	10.9%
Cheaper	57.6%

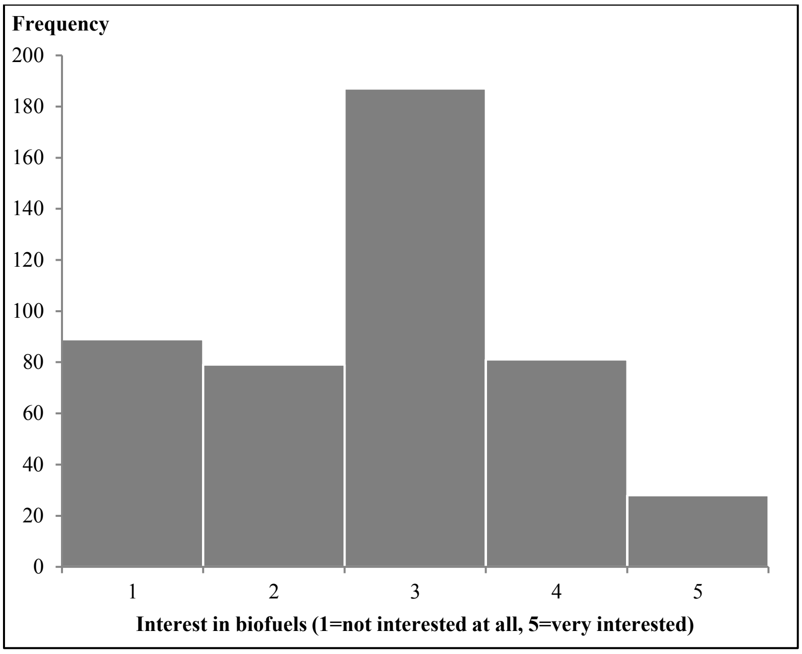
The respondents who admitted not being regular users of biofuels (n=464) were asked a similar question about their lack of support. The multi-choice options (Table 5.12) suggest that the perception that biofuels were not suited or readily available had influenced some respondents to avoid using biofuels. In the open-ended option to the same question, a common thread was the lack of knowledge and understanding of biofuels, with a handful suggesting potential damage to the engine or a lack of relative environmental benefit from biofuels. These findings on the consumer perceptions/knowledge of biofuels are consistent with the literature. (Van de Velde, Verbeke, Popp, Buysse, & Van Huylenbroeck, 2009).

Table 5.12: Reasons for not choosing biofuels.

Reason	% responses
Too expensive	14.0%
Does not give the same performance/not reliable	16.2%
I know/think my vehicle is not suited/recommended for biofuels	33.6%
Not available in my area/local stations	23.1%
Never considered using biofuels	28.9%
No benefit over regular petrol/diesel	9.3%

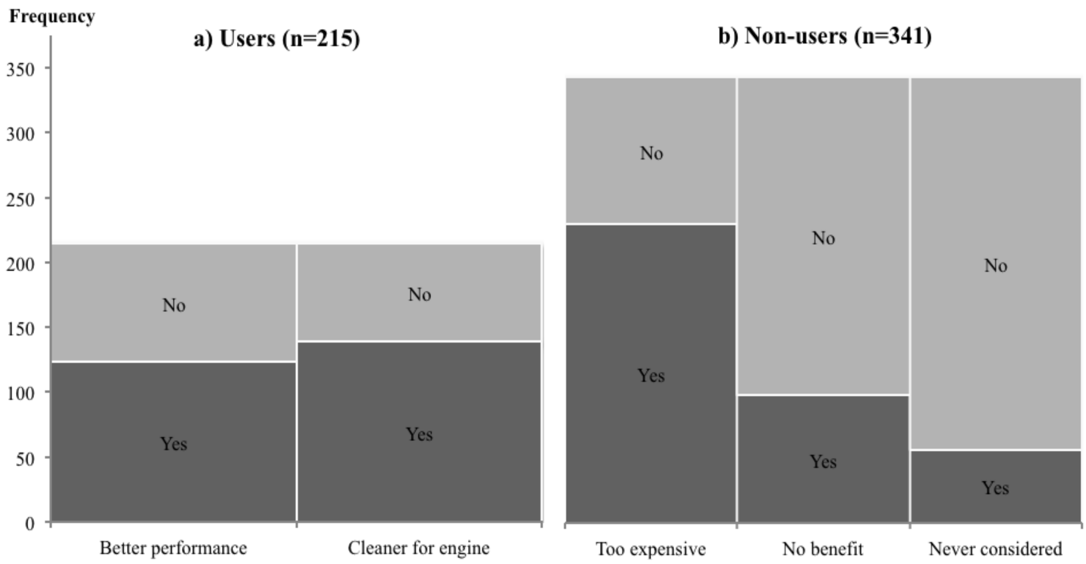
These non-regular users of biofuels were subsequently asked to rank their interest in using biofuels on a Likert-5 scale. Generally, the respondents were found to be low to moderately-interested (between one and three on the five-point scale) with few indicating higher interests (4 or 5) (Figure 5.10).

Figure 5.10: Distribution of respondents' interest in biofuels.



Finally, all respondents were asked if they used premium fuels regularly and the reasons why (or why not) (Figure 5.11). A majority of respondents (61.3%) stated that they did not use premium fuels, primarily because they are too expensive. Some also stated that they were regular diesel users with the perception that no premium diesel fuels were available. Users of premium fuels indicated that these fuels were cleaner for their engine and gave a better performance. However, an interesting finding from the open-ended option to these questions that a number of both users and non-users of premium fuels stated that their choice was on the recommendation of a manufacturer or mechanic, suggesting contrasting information on the benefits of premium fuels based on manufacturer or model of the vehicle, and from respective mechanics.

Figure 5.11: Distribution of respondents who (a) used and (b) did not use premium fuels regularly and why.

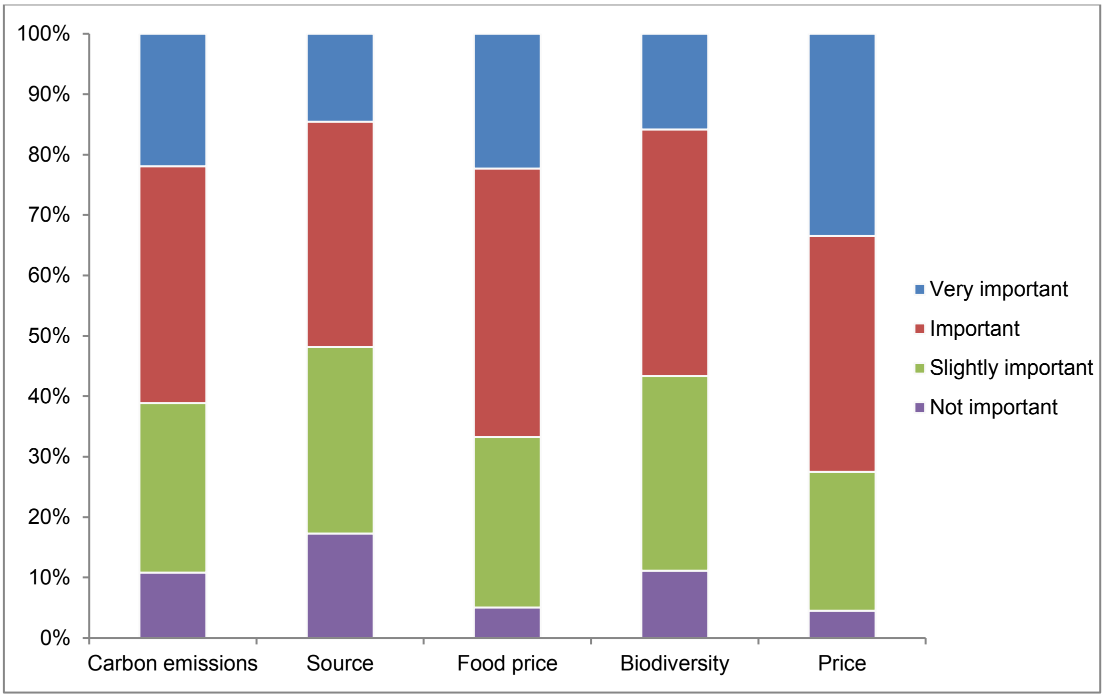


5.4.4. Choice experiment debrief

At the end of the choice experiment, information was collected to understand how choices were made. A parameter was also used to identify if the respondent always chose the status quo option (Biofuel C). It was found that only 6.7% of respondents (n=37) always chose Biofuel C. Similarly, nine and five respondents always chose Biofuel A and Biofuel B respectively. These responses could have been be an indication of protesting the premise in the choice experiment.

The respondents were also asked a series of questions after completing the experiment. These included questions to identify the importance of the attributes to their choices, and if they completely ignored any attribute and why. The distribution of attribute importance as stated by the respondents is shown in Figure 5.12. This distribution shows that generally, the attributes were mostly at least ‘important’ in the respondents’ choices, with fuel price being the most important (highest proportion of ‘important’ and ‘very important’ ratings) for the majority of respondents. Only five respondents reported that all of the attributes were not important to their choices.

Figure 5.12: Distribution of respondents across stated attribute importance.



When asked if they completely ignored any attributes in the entire choice experiment, 20% (n=111) of respondents affirmed this to be the case for their choices. Fuel source was highlighted as the attribute with the highest proportion of these respondents completely ignoring (Table 5.13). A total of 72.1% (n=80) admitted to ignoring only one attribute with only two respondents admitting to ignoring all five attributes in their choices (Table 5.14). A majority (67.6%) of these respondents admitted that they ignored attributes because the attributes were not important or as important as other attributes, with 17.1% agreeing that their ignoring of attributes was due to unrealistic levels of the attribute. The open-ended option to the same question suggests that some respondents would have made choices based only on a single attribute (emissions or fuel source), and even ignoring price.

Table 5.1: Distribution across stated non-attendance to attributes.

Attribute	% responses
Carbon emissions	25.2%
Fuel source	47.7%
Agriculture	26.1%
Biodiversity	30.6%
Price	24.3%

Table 5.2: Distribution across number of attributes non-attended.

Number of attributes	% responses
1	72.1%
2	10.8%
3	9.9%
4	5.4%
5	1.8%

5.4.5. Components used for choice modelling

There were three groups of independent variables used for the choice modelling: (1) the choice attributes, (2) socio-demographic variables, and (3) psychographic variables. The choice attributes were as defined in the previous section on the experiment design, constituting of five attributes with five levels each except for the fuel source that was a dummy of either being local (1) or imported (0). A number of socio-demographic variables were collected through explicit questions in the survey (e.g. age, gender, income). The residing state information was used to partition the models rather than as a dependent variable. Postcode data was collected and used to create a dummy variable to define the respondent being from a metropolitan area using postal area definitions. A dummy variable was created to identify if the respondent was a parent to a dependent child using the information collected on the number of dependent children the respondent had, which itself was used as an independent variable in earlier models. Two separate dummy variables were created to identify the education level of respondents: university graduates and other tertiary (post high-school/Year 12) qualifications. In terms of psychographic variables, the only variable that involved some manipulation was the scaling of weekly fuel expenditure, which was described in the previous section. All variables that were used for the choice modelling analysis are detailed in Table 5.15.

Table 5.15: Variables used in analysis.

Variable	Description	Data type
Choice attributes		
EMISSIONS	Change in net emissions taking into account cultivation and processing relative to Biofuel C.	0.5, 0.75, 1, 1.25, 1.5
SOURCE	Indicator of the source of the fuel, either being completely produced in Australia or partially imported.	0, 1
FOOD PRICE	Estimated impact on food prices from the increased production of the fuel and competition for agricultural resources relative to Biofuel C.	0.8, 0.9, 1, 1.1, 1.2
BIODIVERSITY	Impact on species richness as a result of production of the fuel relative to Biofuel C.	0.5, 0.75, 1, 1.25, 1.5
PRICE	Price of fuel sold relative to Biofuel C.	0.8, 0.9, 1, 1.1, 1.2
Socio-demographic variables		
AGE	Age group of respondent	1 – 7
GENDER	Male gender dummy	0,1
METRO	Dummy identifying respondent from metropolitan areas	0,1
AUSTRALIAN	Dummy identifying if respondent is Australian	0,1
HOUSEHOLD	Count of household size	1 – 9
PARENT	Dummy identifying if respondent is a parent to a dependent child	0,1
CHILDREN	Count of number of dependent children	0 – 6
FUEL INDUSTRY	Dummy identifying if respondent has association with fuel industry	0,1
FARMING	Dummy identifying if respondent has association with farming industry	0,1
UNIVERSITY	Dummy identifying if respondent has at least a bachelor's degree	0,1
OTHER TERTIARY	Dummy identifying if respondent has other tertiary qualifications except university degrees	0,1
STUDENT	Dummy identifying if respondent is currently a student	0,1
INCOME	Income group of respondent[45]	1 – 12
Psychographic variables		
YEARS DRIVING	Number of years respondent has had driver's licence	1 – 70
OWNERSHIP	Number of vehicles respondent owns	0 – 10
WEEKLY HOURS	Average number of hours respondent drives per week	0 – 65
EXPENDITURE	Average weekly expenditure on fuel scaled by how much respondent pays	0 – 562.50
FOSSIL	Dummy identifying if respondent currently uses a (unblended) fossil fuel	0,1
VIEWS	Respondent's perception of their beliefs on a scale of conservatism (10 – most conservative)	1 – 10
MEMBER	Dummy identifying if respondent is a member of an environmental group	0,1

[45] See Table 5.8 for group definition.

Two separate utility functions were specified in the model estimations (as shown at the end of this paragraph). The first would represent the utility of choosing either of the alternatives (Biofuel A or B) and the second would be that of choosing the status quo (Biofuel C). The former would include only the choice attributes (Att_a with coefficient β_a) while the latter would include the Alternative Specific Constant (ASC) to capture any unobserved factors of (Hensher et al., 2005a) the individuals' choices. Hence, a positive ASC would indicate a general preference for the status quo and a negative would suggest preference for the alternatives (Adamowicz et al., 1998a). Socio-demographic and psychographic variables (y) will also be included in the second utility specification when introduced into the estimation.

$$U(A,B)= \sum \beta_a * Att_a$$
$$U(C)=ASC+ \sum \beta_a * Att_a + \sum \beta_y * y$$

All modelling of the DCE sample in this chapter was done using NLogit 5 (Econometric Software Inc., 2012).

5.4.6. Pooled estimations

An MNL model was estimated with the full sample, using only the choice experiment attributes (Appendix F). Although the estimated coefficients were highly significant at 1% and with expected signs, it did not sufficiently identify if the IIA assumption could be held and if the MNL model was appropriate. The Hausman-McFadden (1984) test was carried out by re-estimating MNL models but removing each alternative. Removing two out of the three alternatives (A and B) produced results identifying that the IIA assumption was violated. The model that removed the status quo (Biofuel C) could not run the Hausman-McFadden test (Appendix G). Given the violation of the IIA assumption with the first two alternatives, the less restrictive random parameters logit (RPL) models were considered for the subsequent models.

The RPL model was initially estimated using only choice attributes as a comparison with the MNL estimation. The RPL estimation required that the distribution of the coefficient error terms be defined, with normal distributions being most common (Hensher et al., 2005a). A number of models were estimated using different distribution combinations for the error terms of choice attributes and compared according to model fit using AIC. The model that used normal distributions for all attributes except fuel price, which used a triangular distribution, had the best/lowest AIC (Table 5.16). Using triangle distributions for the payment/cost attribute error term in an RPL model for choice modelling is common in the literature (Greene & Hensher, 2003; Hensher & Greene, 2003; Scarpa, Zanoli, Bruschi, & Naspetti, 2013). The RPL estimation also allowed for the panel nature of the data as each respondent completed eight choice tasks. In a comparison with the MNL estimation, the RPL model had a lower AIC and higher adjusted-R^2, and still maintained highly significant (at 1%) attributes with expected signs.

Table 5.16: Panel-RPL estimation for pooled sample with only choice attributes.

Variable	Coeff.		S.E.	Dist.
EMISSIONS	-1.832	***	0.105	n
SOURCE	0.895	***	0.080	n
FOOD PRICE	-4.065	***	0.246	n
BIODIVERSITY	1.344	***	0.097	n
PRICE	-4.160	***	0.246	t
ASC	0.755	***	0.059	
N	556			
Adj. R^2	0.178			
LL	-4886.6			
AIC	1.808			

'***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%

Subsequently, a number of models were estimated to incorporate the socio-demographic and psychographic variables listed in Table 5.15. Variables were progressively dropped based on level of significance and improvements to model fit by AIC. Different distributions of the attributes' coefficients were also attempted and estimation with all normal distributions was found to result in the model with the best AIC[46]. The estimation of the panel-RPL model incorporating the six socio-demographic variables and two psychographic variables that were significant at least at a 10% level[47] is shown in Table 5.17. The WTP estimates were derived using equation 5.12.

[46] Testing the model performance based on changes in distributions of the error term was attempted for all subsequent panel-RPL models. However, estimations that used a normal distribution across all attributes were consistently found to result in the best model fit by AIC.

[47] A similar process was carried out with MNL estimations. The same variables were found to be significant (Appendix F). However, based on the reasons mentioned above, the panel-RPL estimation was used instead as the base model.

Table 5.17: Panel-RPL and WTP estimations for pooled sample.

Variable	Coeff.		S.E.	Dist.	WTP
Choice attributes					
EMISSIONS (+25%)	-1.922	***	0.110	n	-0.453
SOURCE	0.903	***	0.084	n	0.213
FOOD PRICE (+10%)	-4.357	***	0.268	n	-1.026
BIODIVERSITY (+25%)	1.365	***	0.102	n	0.321
PRICE	-4.247	***	0.258	n	
ASC	0.810	***	0.247		
Socio-demographic variables					
AGE	0.106	***	0.028		
GENDER	-0.239	***	0.092		
PARENT	0.176	*	0.097		
FUEL INDUSTRY	-0.874	***	0.289		
OTHER TERTIARY	0.294	***	0.098		
INCOME	-0.119	***	0.022		
Psychographic variables					
FOSSIL	0.272	**	0.126		
MEMBER	-0.660	***	0.212		
N	556				
Num of obs.	4448				
Adj. R^2	0.190				
LL	-4886.6				
AIC	1.784				

'***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%

5.4.7. Protest responses

There was the potential for respondents to protest with the premise of the DCE (see section 5.4.4). Although separate questions were not included to collect this information, an assumption was made that respondents choosing the same alternative throughout, despite varying levels of the attributes, would suggest either protest to the experiment or lack of consideration of the varying attributes in the experiment. Hence, models were run dropping respondents who chose the same options for each choice exercise. The numbers of such respondents were proportionately low (nine always choosing A, five always choosing B, and 37 always choosing C) and initial presumptions were that there would not be significant improvements from treating these respondents. However, when separate models were run for each case of protest, the models performed better when comparing the AIC and adjusted-R^2 (Appendix H). Hence, all responses that indicated protest in this manner (n=51) were dropped and the panel-RPL was re-estimated accordingly with the same variables (Table 5.18).

Table 5.18: Panel-RPL and WTP estimation excluding protestors.

Variable	Coeff.		S.E.	WTP
Choice attributes				
EMISSIONS (+25%)	-1.917	***	0.112	-0.455
SOURCE	0.995	***	0.081	0.236
FOOD PRICE (+10%)	-4.346	***	0.275	-1.032
BIODIVERSITY (+25%)	1.346	***	0.105	0.320
PRICE	-4.212	***	0.267	
ASC	0.624	**	0.259	
Socio-demographic variables				
AGE	0.064	**	0.029	
GENDER	-0.094		0.097	
PARENTS	0.201	**	0.101	
FUEL INDUSTRY	-1.053	***	0.337	
OTHER TERTIARY	0.240	**	0.102	
INCOME	-0.104	***	0.023	
Psychographic variables				
FOSSIL	0.195		0.127	
MEMBER	-0.989	***	0.239	
N	505			
Adj. R^2	0.202			
LL	-4438.4			
AIC	1.758			

'***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%

The model fit based on the adjusted-R^2 is below the broadly suggested ideal 0.3-0.4 minimum range (Greene, 2012), but this is not uncommon in DCE modelling. The choice attributes, in particular, were found to be highly significant at 1% and with expected signs. A more positive EMISSIONS, FOOD PRICE, and fuel PRICE negatively affected respondents' preferences for the option and WTP; conversely, a fuel that is made in Australia (SOURCE=1) and had a positive effect on BIODIVERSITY had a positive effect on their preferences and WTP. The magnitude of the coefficient for FOOD PRICE suggested it had the greatest marginal effect on preferences, even more so than the fuel PRICE. The WTP estimate suggested that respondents on average were willing to pay more than double (103% more) their fuel PRICE to avoid a 10% increase in food prices. Using the average weekly scaled expenditure on fuel of $34.68 (derived in section 5.4.3) and the average individual weekly expenditure on food and non-alcoholic drinks $141.24[48] (Australian Bureau of Statistics, 2011c, Table 29), this WTP of $35.79 is higher than the reduction to food prices at $14.12. This could suggest respondents overestimated their expenditure on food resulting in irrational preference for this attribute or perhaps overstated their WTP. Reducing EMISSIONS had the second highest WTP at 45% to reduce emissions by 25%. The SOURCE of the fuel had the lowest WTP, at 21% more for a locally-produced fuel.

The positive ASC indicated that respondents had a greater preference for the status quo option. The coefficients of the socio-demographic and psychographic variables indicated how this preference would change. If a respondent was older (AGE), a PARENT, had OTHER TERTIARY education, or was an existing FOSSIL fuel user; they were more likely to choose the status quo option. Conversely, if the respondent had association with the FUEL INDUSTRY, had a higher INCOME, or was a MEMBER of an environmental group, they were less likely to choose the status quo and instead pick one of the two alternative fuels. While most of the signs for these coefficients were as expected, the estimate for the FUEL INDUSTRY parameter was not, given the presumption that such an individual would prefer a status quo option rather than paying for a new alternative. It also had the highest marginal effect on the choice between the status quo and alternative options.

[48] Future iterations of this study could collect stated responses from respondents on their estimated weekly expenditure on food to give a more accurate reflection of the rationality of their tradeoffs.

This model that excluded protestors showed the same signs and high levels of significance for the choice attributes; with relatively similar coefficient estimates to the pooled panel-RPL estimation (Table 5.17). Also the signs for the socio-demographic and psychographic variables were the same, although the significance changed across a number of attributes. On dropping protestors, AGE and OTHER TERTIARY were less significant compared to the previous model, with PARENT becoming more significant. GENDER and FOSSIL were found insignificant (at least at a 10% level) to the ASC but dropping these from the specification decreased the model performance in terms of AIC and adjusted-R^2.

Despite the small proportion, the presence of protestors was found to affect the results. There were minimal differences in estimates for the choice attributes and generally similar signs of other variables. However, protest responses did affect the significance of a number of variables, resulted in lower WTP estimates, and negatively affected the model performance. Hence, the estimation shown in Table 5.18 will be treated as the 'base' model for the pooled sample. Subsequent models will similarly exclude protestors[49].

5.4.8. Partitioning by state

Although the panel-RPL model accounted for some heterogeneity, further estimations were attempted to assess if the choices could be better modelled to account for heterogeneous preferences. The first set of models was to assess if current state-based policies on biofuels could influence consumer preferences. This was done by partitioning the sample by state and running panel-RPL models for each sub-sample. These models would allow comparisons between respondents in NSW, which had existing biofuel mandates, and other states that may

[49] Models incorporating partitioning and attribute non-attendance were run to include protestors and to compare with the respective models in this chapter. These can be found in Appendix I.

(QLD[50], VIC) or may not be in the process of establishing biofuel policies. The sub-sample sizes for ACT, NT, SA, and TAS were too small and models could not be estimated. The models for the remaining states with WTP estimates are shown in Table 5.19.

For all the models, the choice attributes were highly significant at 1% and with expected signs. The significance of the socio-demographic and psychographic variables varied across the models with most not being significant even at a 10% level. Those that were significant exhibited signs consistent with the base model (in Table 5.18). Dropping insignificant variables worsened the models' fit and hence, they were maintained in the results.

There were some key differences when considering the WTP estimates for different attributes. In particular, the estimations suggest that respondents from WA had a higher WTP for all attributes than other states, notably with EMISSIONS being double that of the next highest estimate from VIC. The estimates also suggest that despite being the only state with biofuel mandates (at time of survey), there was no remarkable difference in the WTP between NSW and QLD or VIC; with the latter two states having had discussions on similar policies at the time. Hence, it can be suggested that the three eastern states had relatively similar preferences in regards to the attributes in the choice experiment as compared to WA, which showed a stronger preference for changes across the same attributes. This was unexpected, given the lack of policy surrounding biofuels being discussed or introduced in the state, compared to its eastern counterparts.

[50] At the time of the survey, QLD had not yet implemented its biofuel mandate policy. Hence, in this section, reference to QLD as a state without existing mandate policy will be made.

Table 5.19: Panel-RPL and WTP estimation partitioned by state†.

	NSW				VIC				QLD				WA			
Variable	Coeff.		S.E.	WTP	Coeff.		S.E.	WTP	Coeff.		S.E.	WTP	Coeff.		S.E.	WTP
Choice attributes																
EMISSIONS (25%)	-1.671	***	0.167	-0.435	-1.970	***	0.220	-0.432	-2.018	***	0.312	-0.360	-2.002	***	0.530	-0.902
SOURCE	0.779	***	0.124	0.203	1.175	***	0.162	0.258	1.272	***	0.241	0.227	0.854	***	0.297	0.385
FOOD PRICE (10%)	-3.461	***	0.394	-0.901	-4.505	***	0.535	-0.988	-6.170	***	0.889	-1.099	-3.522	***	0.924	-1.588
BIODIVERSITY (25%)	1.169	***	0.175	0.304	1.326	***	0.206	0.291	1.543	***	0.295	0.275	1.098	***	0.361	0.495
PRICE	-3.843	***	0.414		-4.560	***	0.531		-5.613	***	0.787		-2.218	**	1.035	
ASC	0.509		0.424		0.483		0.462		0.720		0.850		2.978	*	1.757	
Socio-demographic variables																
AGE	0.065		0.047		0.167	***	0.055		0.014		0.083		-0.037		0.142	
GENDER	-0.007		0.170		-0.285		0.183		-0.326		0.272		0.412		0.422	
PARENT	0.028		0.175		0.142		0.204		0.427	*	0.244		0.693	*	0.397	
FUEL INDUSTRY	-2.276	**	1.061		0.026		0.503		-2.721	***	0.882		0.115		1.328	
OTHER TERTIARY	0.033		0.176		0.593	***	0.220		0.740	***	0.264		-0.028		0.407	
INCOME	-0.108	***	0.038		-0.049		0.043		-0.004		0.063		-0.292	**	0.123	
Psychographic variables																
FOSSIL	0.068		0.171		0.233		0.303		0.315		0.411		-1.983		1.394	
MEMBER	-0.979	**	0.423		-1.329	***	0.423		-0.147		0.660		-2.039	*	1.220	
N	167				137				96				41			
Adj. R^2	0.188				0.195				0.215				0.205			
LL	-1467.7				-1204.1				-843.7				-360.3			
AIC	1.800				1.788				1.754				1.812			

†Excluding ACT, NT, SA, and TAS. '***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%

5.4.9. Partitioning by income

The next category for partitioning was by income. Although the INCOME variable identified the effect of income levels on the likelihood of choosing an alternative (A or B) over the status quo (C), it did not identify a relationship with the marginal values of the choice attributes. The income-based partitioning would have been relatively straight forward given the income groups as defined in Table 5.8. However, having a large number of groups reduces the model fit and explanatory power. Also, separate models for some income groups (i.e. nil income and higher earners above $104,000 p.a.) could not be estimated due to the small sub-sample sizes. Hence, those that reported no income were dropped and high income earners (Groups 7-12) were collated into a single group (Table 5.20). A separate panel-RPL was then estimated for each sub-sample (Table 5.21).

Table 5.20: Income groups for partitioning by income.

Income group	Income ranges
Group 2	$1 - $20,799
Group 3	$20,800 - $41,599
Group 4	$41,600 - $64,999
Group 5	$65,000-$77,999
Group 6	$78,000-$103,999
Group 7+	$104,000 or more

All the income-partitioned estimations had an adjusted-R^2 of at least 0.20 except for Group 6. All the choice attribute coefficients remained highly significant at 1% with expected signs. The significance of the socio-demographic and psychographic variables varied across the models; these variables were still kept in the final estimation, as dropping them reduced the model fit by AIC and adjusted-R^2.

Table 5.21: Panel-RPL estimations partitioned by income groups‡.

	Group 2			Group 3			Group4			Group 5			Group 6			Group 7+		
Variable	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.
Choice attributes																		
EMISSIONS	-1.985	***	0.323	-2.263	***	0.247	-2.207	***	0.256	-2.587	***	0.601	-1.193	***	0.263	-1.751	***	0.310
SOURCE	1.335	***	0.217	1.164	***	0.187	0.884	***	0.168	1.223	***	0.330	0.781	***	0.196	0.727	***	0.190
FOOD PRICE	-5.441	***	0.716	-5.572	***	0.601	-4.965	***	0.639	-4.993	***	1.057	-2.044	***	0.581	-3.869	***	0.800
BIODIVERSITY	1.538	***	0.264	1.580	***	0.241	1.266	***	0.253	1.269	***	0.459	1.070	***	0.246	1.270	***	0.308
PRICE	-3.259	***	0.652	-5.337	***	0.676	-4.927	***	0.611	-4.845	***	1.363	-2.405	***	0.522	-4.420	***	0.781
ASC	-0.471		0.558	0.406		0.510	0.117		0.543	-4.047	***	1.540	-0.566		0.750	0.157		0.883
Socio-demographic variables																		
AGE	0.099		0.061	0.158	***	0.059	0.063		0.067	0.401	***	0.151	0.067		0.098	0.037		0.126
GENDER	0.182		0.226	-0.199		0.218	-0.184		0.224	0.272	***	0.443	0.073		0.263	-0.001		0.350
PARENTS	-0.128		0.264	0.271		0.248	-0.160		0.231	0.609		0.436	-0.242		0.275	0.655	**	0.287
FUEL INDUSTRY	-50.33		$2.63E^{10}$	-2.832	**	1.324	0.075		0.725	-46.143		$2.95E^{10}$	-0.782		0.695	-1.056	*	0.573
OTHER TERTIARY	0.546	**	0.240	0.059		0.217	0.492	**	0.220	-0.815	*	0.466	0.519	*	0.295	0.743	**	0.374
Psychographic variables																		
FOSSIL USER	0.620	**	0.309	0.005		0.274	0.424		0.282	2.974	***	1.133	0.315		0.442	-0.694	*	0.395
MEMBER	0.049		0.557	1.149		0.942	-1.069	**	0.469	-1.579		1.267	-2.134	**	1.069	-0.580		0.559
N	102			105			90			44			63			62		
Adj. R^2	0.203			0.213			0.225			0.248			0.145			0.228		
LL	-896.5			-922.8			-791.0			-386.7			-553.7			-544.9		
AIC	1.776			1.753			1.731			1.712			1.917			1.739		

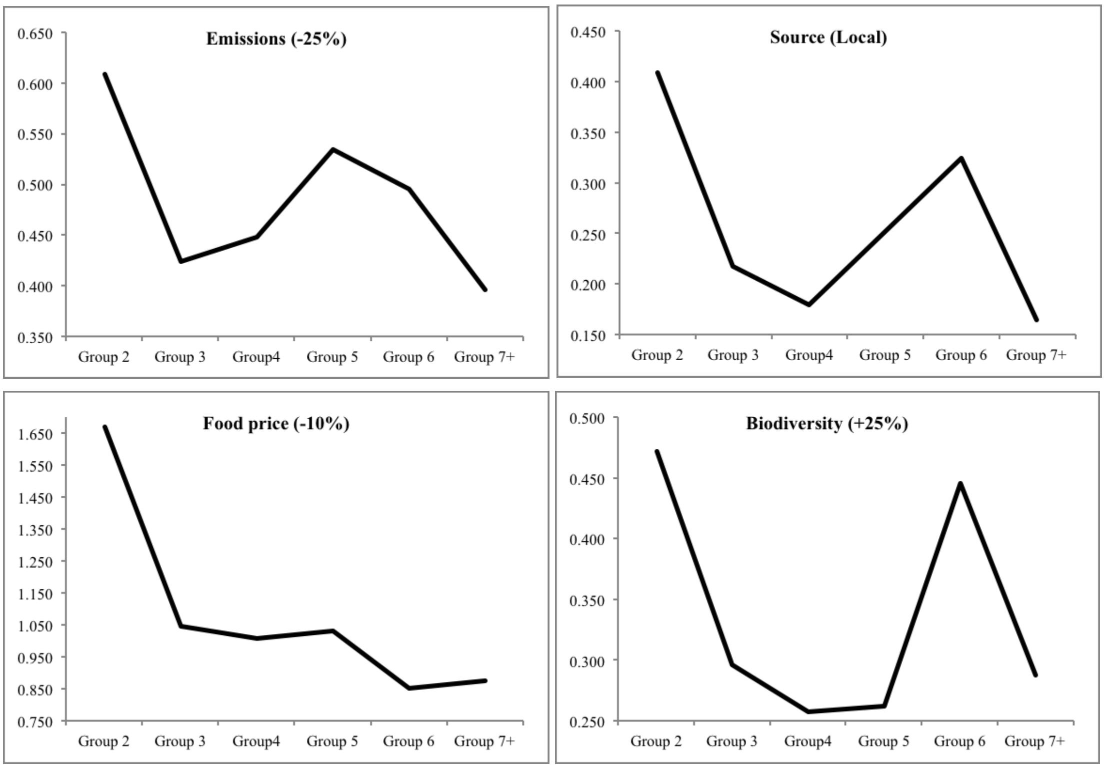
‡Excluding Group 1. E^n is exponential to the n^{th} power. '***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%.

Estimation of the marginal WTP highlighted some key findings that were unexpected (Table 5.22 and Figure 5.13). Based on the results from the pooled estimation, it was assumed that individuals with higher incomes would have higher WTP for improvements across the various attributes as they were expectedly found to more likely choose an alternative over the status quo. However, the estimations revealed that the lowest income group (Group 2) had the highest WTP estimates across all the attributes. In particular, these respondents were found to have a WTP for FOOD PRICE almost double that of higher income earners (Groups 6 and 7+).

Table 5.22: Marginal WTP estimates for groups partitioned by income.

Attribute	Group 2	Group 3	Group4	Group 5	Group 6	Group 7+
EMISSIONS (+25%)	-0.609	-0.424	-0.448	-0.534	-0.496	-0.396
SOURCE	0.410	0.218	0.180	0.252	0.325	0.164
FOOD PRICE (+10%)	-1.670	-1.044	-1.008	-1.030	-0.850	-0.875
BIODIVERSITY (+25%)	0.472	0.296	0.257	0.262	0.445	0.287

Figure 5.13: Marginal WTP from partitioning by income.



Further investigation on the presence of heterogeneity was conducted using an LCM for the choice attributes and by running separate choice probability probit models. However, the results suggested the best model from a large number of classes, and the estimates were unrealistic and difficult to interpret (Appendix J).

5.4.10. Stated non-attendance

As previously mentioned, non-attendance to attributes is a major issue in choice experiments. In this study, both stated and inferred methods of modelling non-attendance were attempted. For the stated non-attendance (SNA) models, the information collected in the survey on respondents self-reporting that they ignored the attributes was used to identify non-attendance. Following Kragt's (2013) method for coding SNA, "-888" was coded for attributes that respondents admitted to not attending to. The five separate models for SNA to each attribute individually is given in Table 5.23.

The models that accounted for SNA to EMISSIONS and BIODIVERSITY were the only models to perform marginally better than the base model in Table 5.18, according to the AIC and adjusted-R^2. None of the estimated coefficients were remarkably different from the base model, although the significance of the socio-demographic and psychographic variables varied across the models. While initial inferences would suggest that respondents accurately identified non-attendance to these two attributes compared to the others, the marginal improvement from the base model does not suggest this as a concrete finding.

Instead, a number of subsequent models were estimated to incorporate SNA to multiple attributes simultaneously. This process found that despite individual SNA models expectedly indicating that SNA to PRICE may not have occurred (like in Balcombe et al., 2011), the estimation accounting for SNA to EMISSIONS, BIODIVERSITY, and PRICE produced the best model by AIC and adjusted-R^2 (Table 5.24). The estimated coefficients were again not remarkably different from the base mode with model fit diagnostics being only marginally better. This suggests that ANA might have occurred at some level but the SNA data was not sufficient to identify the extent of ANA i.e. individual reporting of ANA might not be accurate.

Table 5.23: Panel-RPL for SNA to choice attributes.

	SNA – EMISSIONS (n=25)			SNA – SOURCE (n=45)			SNA - FOOD PRICE (n=24)			SNA – BIODIVERSITY (n=31)			SNA - PRICE (n=22)		
Variable	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.
Choice attributes															
EMISSIONS	-1.957	***	0.114	-1.880	***	0.112	-1.893	***	0.112	-1.910	***	0.114	-1.896	***	0.111
SOURCE	0.999	***	0.082	0.879	***	0.080	0.988	***	0.081	1.018	***	0.083	0.982	***	0.080
FOOD PRICE	-4.271	***	0.268	-4.303	***	0.272	-4.409	***	0.279	-4.358	***	0.273	-4.268	***	0.272
BIODIVERSITY	1.383	***	0.105	1.286	***	0.102	1.340	***	0.106	1.459	***	0.110	1.345	***	0.105
PRICE	-4.077	***	0.264	-4.088	***	0.258	-4.207	***	0.271	-4.114	***	0.268	-4.368	***	0.275
ASC	0.604	***	0.259	0.511	***	0.252	0.631	**	0.259	0.630	**	0.259	0.619	**	0.259
Socio-demographic variables															
AGE	0.063	***	0.029	0.054	***	0.028	0.063	**	0.029	0.063	**	0.029	0.064	**	0.029
GENDER	-0.092	**	0.097	-0.088	***	0.095	-0.096		0.097	-0.093		0.097	-0.095		0.097
PARENT	0.205	*	0.101	0.192	*	0.099	0.204	**	0.101	0.206	**	0.101	0.202	**	0.101
FUEL INDUSTRY	-1.054	***	0.341	-0.953	***	0.338	-1.107	***	0.337	-1.066	***	0.341	-1.055	***	0.337
OTHER TERTIARY	0.249	***	0.103	0.248	***	0.101	0.240	**	0.102	0.243	**	0.103	0.245	**	0.103
INCOME	-0.102	***	0.023	-0.100	***	0.022	-0.104	***	0.023	-0.103	***	0.023	-0.104	***	0.023
Psychographic variables															
FOSSIL	0.200	**	0.127	0.219	**	0.124	0.192		0.127	0.196		0.128	0.197		0.127
MEMBER	-0.973	***	0.239	-0.965	***	0.237	-0.999	***	0.239	-0.980	***	0.240	-0.994	***	0.240
N	505			505			505			505			505		
Adj. R^2	0.203			0.195			0.201			0.203			0.192		
LL	-4438.4			-4438.4			-4438.4			-4438.4			-4886.6		
AIC	1.757			1.774			1.761			1.757			1.781		

'***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%

Table 5.24: Panel-RPL and WTP estimations for SNA to EMISSIONS, BIODIVERSITY, and PRICE.

Variable	Coeff.		S.E.	WTP
Choice attributes				
EMISSIONS (+25%)	-1.939	***	0.114	-0.458
SOURCE	0.982	***	0.081	0.232
FOOD PRICE (+10%)	-4.215	***	0.267	-0.996
BIODIVERSITY (+25%)	1.419	***	0.108	0.335
PRICE	-4.230	***	0.271	
ASC	0.599	***	0.258	
Socio-demographic variables				
AGE	0.062	***	0.029	
GENDER	-0.090	**	0.097	
PARENT	0.207	*	0.101	
FUEL INDUSTRY	-1.053	***	0.340	
OTHER TERTIARY	0.249	***	0.103	
INCOME	-0.103	***	0.023	
Psychographic variables				
FOSSIL	0.199	**	0.127	
MEMBER	-0.987	***	0.239	
N	505			
Adj. R^2	0.205			
LL	-4438.4			
AIC	1.753			

'***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%

5.4.11. Inferred non-attendance

Given the findings from the SNA analysis, INA was also attempted using panel-latent class modelling (LCM). The panel-LCM estimation was run for the choice attributes alone, without socio-demographic and psychographic variables. A seven-class panel-LCM was estimated to cover non-attendance to each attribute, full attendance, and full non-attendance by restricting the respective parameters to zero. However, the full attendance class was found to have a zero class probability (i.e. suggesting there was no respondent who paid full attention to all attributes) and dropping it from estimation did not affect the model fit or coefficient estimates for other classes (Table 5.25). All remaining probability classes were also highly significant at 1%.

In terms of model fit, this INA panel-LCM was marginally worse than the 'base' panel-RPL run with only choice attributes (Appendix K) by both AIC and adjusted-R^2.

The class probability component of the results suggests that 16.4% of respondents may have ignored all attributes in their decision-making, even when protest responses were dropped. However, when the same estimation was carried out to include the protest responses (see Table I.3); the percentage of respondents in this group was higher at 24.8%. This suggested that removing protestors could have accounted for some individuals who did not pay attention to all attributes when making their decision i.e. by choosing the same option in all choice sets, the respondents were either protesting the context of the experiment, or choosing not to attend to the attributes and choosing randomly. The percentage difference (8.4%) was also similar to the sub-sample size highlighted as protestors (9.2%).

The estimation indicated that 48.5% of the sample ignored SOURCE. This was similar to the reported ANA data that SNA to SOURCE was the highest, although at a much lower proportion than estimated from the INA modelling by over five times. This was consistent with the second highest proportion (excluding total INA) of responses ignoring BIODIVERSITY, although this was double the proportion of that identified in the SNA estimation. This did not follow in the rankings of the remaining three attributes.

The model fit of these separate probit regressions were assessed based on the p-value of the Hosmer-Lemeshow (1980) statistic, which suggested that at a 5% level, all of the probit regressions show no signs of a lack of fit. However, the estimated coefficients for Classes 2, 5, and 6 were all not significant, suggesting it would be hard to determine the likely characteristics of those ignoring the respective attributes. Of the remaining classes, the estimation found that AGE and GENDER were negatively related to the class probability i.e. if a respondent was older or male, they were less likely to exhibit INA to the attributes.

Table 5.25: Panel-LCM for INA to choice attributes.

	Class 1 EMISSIONS NA			**Class 2 SOURCE NA**			**Class 3 FOOD PRICE NA**			**Class 4 BIODIVERSITY NA**			**Class 5 PRICE NA**			**Class 6 Full NA**		
Variable	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.
EMISSIONS	0.000		fixed	-2.029	***	0.112	-2.029	***	0.112	-2.029	***	0.112	-2.029	***	0.112	0.000		fixed
SOURCE	1.955	***	0.124	0.000		fixed	1.955	***	0.124	1.955	***	0.124	1.955	***	0.124	0.000		fixed
FOOD PRICE	-4.819	***	0.285	-4.819	***	0.285	0.000		fixed	-4.819	***	0.285	-4.819	***	0.285	0.000		fixed
BIODIVERSITY	1.666	***	0.122	1.666	***	0.122	1.666	***	0.122	0.000		fixed	1.666	***	0.122	0.000		fixed
PRICE	-4.821	***	0.289	-4.821	***	0.289	-4.821	***	0.289	-4.821	***	0.289	0.000		fixed	0.000		fixed
Class probability	0.059	***	0.021	0.485	***	0.035	0.081	***	0.025	0.125	***	0.030	0.086	***	0.027	0.164	***	0.027
N	505																	
Adj. R^2	0.190																	
LL	-4438.4																	
AIC	1.782																	
							Class membership probit models											
Variable	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.
Socio-demographic variables																		
AGE	-0.100	**	0.045	0.012		0.029	-0.096	**	0.041	-0.070	*	0.036	-0.097		0.040	-0.089		0.035
GENDER	-0.405	***	0.137	0.010		0.088	-0.344	***	0.124	-0.243	**	0.111	-0.229		0.121	-0.402		0.107
PARENT	-0.112		0.198	0.036		0.123	-0.178		0.180	0.037		0.155	-0.150		0.175	0.068		0.146
FUEL INDUSTRY	-0.453		0.671	-0.446		0.349	-0.033		0.430	-0.337		0.465	-0.206		0.479	0.736		0.339
OTHER TERTIARY	-0.128		0.205	0.078		0.126	-0.307		0.199	-0.067		0.161	-0.100		0.180	0.063		0.152
INCOME	-0.035		0.040	-0.008		0.025	-0.004		0.034	-0.056	*	0.032	-0.069		0.036	-0.030		0.030
Psychographic variables																		
FOSSIL	-0.315		0.203	-0.088		0.141	-0.369	**	0.187	-0.269		0.171	-0.266		0.187	0.062		0.173
MEMBER	-0.027		0.412	-0.384		0.243	0.438		0.290	0.324		0.282	0.421		0.294	-0.072		0.298
LL	-119.1			-349.8			-147.0			-195.9			-155.0			-225.4		
AIC	0.503			1.403			0.614			0.807			0.645			0.9		
Hosmer-Lemeshow	12.114			2.829			9.762			11.415			14.083			9.267		
P-value	0.146			0.945			0.282			0.179			0.080			0.320		

'***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%

The INA to SOURCE was found to result in a much lower WTP compared to when INA was accounted for (Table 5.26) by as much as 1.7 times.

Table 5.26: Marginal WTP for regular and INA estimations.

Attributes	Regular	INA
EMISSIONS (+25%)	-0.470	-0.421
SOURCE	0.236	0.405
FOOD PRICE (+10%)	-1.028	-1.000
BIODIVERSITY (+25%)	0.336	0.346

5.5. Discussion

5.5.1. Findings and contributions from analysis

The DCE study had identified several key findings in the given context. The results show that consumers exhibited a high WTP in regards to these externalities relative to the fuel. In particular, the impacts of increased biofuel production on food price garnered the highest marginal WTP value of over 100% of the fuel price. If made aware, consumers also exhibited a significant WTP for reducing impacts of higher emissions and biodiversity loss. The origin of where the fuel was produced was found to be least important to consumers, but the WTP values were `still highly significant and represented a considerable proportion of fuel prices.

The estimates for WTP for emissions reduction was comparably much higher than other studies by as much as 20 times (Fimereli & Mourato, 2009; Khachatryan et al., 2011), possibly due to the exclusion of practical aspects of the fuels. In a study that compared only externalities, the estimates for emissions was still much higher although, impacts to biodiversity was more similar (about double) (Susaeta et al., 2010). This could be the result of a number of differences with the approach in the DCE design e.g. dichotomous versus three choice options, availability of a status quo as reference, number of attributes, effects of labelling on responses.

The much higher WTP for reduced emissions and seemingly irrational WTP for reduced impacts to food prices could suggest inflated WTP reported by respondents. While this leaves questions on the actual magnitude of benefit values, the values estimated can still be relevant in a discussion of the economic value of different biofuel feedstocks when used in a relative comparison across the feedstocks. It also indicates opportunities for future studies, which will be discussed in the next section.

State-based partitioning of the sample illustrated that for the most part, consumers across the three most populous states in Australia had relatively homogenous preferences for the externalities of biofuels. However, respondents from WA were found to exhibit a higher WTP across the attributes compared to the other states. This represented an unexpected finding. WA was the only state out of the four more populous states that had not introduced any biofuel-related policy (e.g. mandates) into discussions and consumers were assumed to have a lower WTP.

Similarly, partitioning by income revealed that the lowest income group (of those with reported incomes) had the highest WTP across all attributes. This was contradictory to assumptions that those with higher incomes would be more willing to pay for the external benefits, which was also inferred from the pooled estimations that indicated higher incomes increased the likelihood of choosing an alternative biofuel over the status quo. Respondents from higher income groups were also found to have the lowest WTP across three out of the four non-price attributes.

In attempting to ascertain the impacts of potential ANA, both SNA and INA methods were employed. The results from the SNA modelling were generally inconclusive both in terms of model fit and attribute coefficients. However, it did suggest that ANA would have occurred, although SNA may not have adequately captured these effects. This statement was supported by the findings from the INA analysis. It found that respondents did ignore at least one attribute, with SOURCE having the highest proportion of INA. Although this was consistent with the reported SNA, the proportion of respondents in this group was more than five times higher than reported in the SNA responses.

5.5.2. Implications from results

Supply-focused studies have identified the importance of feedstock availability to the development of specific biofuel production, particularly in Australia (Kosinkova et al., 2015a). However, this study finds that there are potential external economic benefits and costs from development of certain feedstocks, particularly if they affect food prices. Previous literature has identified that consumers have a WTP for alternative energy in transport when holding practical aspects constant (Mabit & Fosgerau, 2011). The findings from this DCE elaborate that in such instances when consumers were faced with biofuels with similar practical characteristics, they had WTP for, and made trade-offs between, the externalities associated with the respective biofuels. This could be a realistic scenario given policy support for biofuels through mandates, and biofuel-blends will force similar performance and access of biofuels. Hence, the value of the externalities of the biofuel (and production) could define the efficiency of public investment in developing one feedstock over another.

The results indicate the highest WTP to reducing impacts on food price. The review in Chapter 2 had identified that the literature does not reach a strong consensus on relationship between increased biofuel consumption and food prices given current marginal use of biofuels in the subject markets (often in USA). However, it was a reasonable assumption that with an increased dependence on conventional biofuels derived from terrestrial feedstock, the competition for land and other agricultural resources (including crops) could impact the supply and resulting price of food. The analysis has shown that consumers were willing to pay more than twice their regular fuel prices to avoid a comparably smaller (10%) increase in food prices (or to see a similar decrease in food prices), a potentially irrational amount when accounting for actual expenditure. Additionally, the study found that consumers also had a significant WTP for environmental impacts of biofuels i.e. emissions and impacts to biodiversity.

A comparison of the economic value across different feedstocks can be made using these values (Table 5.27). First generation biofuels have the highest potential impacts to food prices (due to competition for crops and agricultural resources), net emissions (due to large carbon debts), and also high impacts to biodiversity (from land clearing); the only key benefit being the ability to produce part of the total fuel requirements domestically. In comparison, second generation biofuels could have lower impacts to food price (due to a decrease in competition for food crops) and have a greater propensity to meet fuel demands through higher local production. Third generation biofuels outperform their predecessors across all these categories due to the lack of competition (and potentially reduction in pressure) for crops and agricultural resources, avoidance of land clearing that affects net emissions and biodiversity, and highest potential for meeting fuel demands through local production of fuel. Also, bio-fixation of waste effluents can have a positive benefit on the net emissions of the technology. Hence, third-generation biofuels can have the highest non-market value among the current biofuel feedstocks.

Table 5.27: Conceptual non-market value estimates§.

Attribute	First generation	Second generation	Third generation
Impacts to food price	Highly negative impacts through food and agricultural resource competition (2.2.6)	Negative impacts through agricultural resource competition (2.2.6)	Positive impacts due to reduced pressure on crop and agricultural resources (2.3.5)
Net emissions	Highly negative impacts from carbon debts from land clearing (2.2.4)	Highly negative impacts from carbon debts from land clearing (2.2.4)	Positive impacts from lack of land clearing and benefits from bio-fixation (2.3.3)
Impacts to biodiversity	Highly negative impacts to biodiversity from land clearing/conversion (2.2.4)	Highly negative impacts to biodiversity from land clearing/conversion (2.2.4)	No need for land clearing/conversion (2.3.5)
Local production	Potential for local production to meet part of demand	Potential for local production to meet larger part of demand	Potential for local production to meet to meet entire demand through high growth efficiency (2.3)
Non-market value	Low	Moderate	High

§Numbers in brackets correspond to sections in 0.

These findings will prove consequential to policymakers considering the development of biofuel feedstocks in Australia. If policy and technological developments were to result in similar practical aspects across the biofuels, the high non-market value of third-generation (i.e. microalgae) biofuels warrants public investment to ensure the greatest social benefit. A low estimate for the economic value for such biofuels that reduce pressure on food prices, reduce overall emissions, and support biodiversity, was more than twice the regular fuel price. These estimates could justify the efficiency of the public investment, particularly through subsidies and/or tax incentives.

However, production estimates (like those estimated in Chapter 3) did suggest that this might be insufficient for alternative biofuels to be produced at a unit price that would be competitive with conventional biofuels or fossil fuel counterparts. Rather, internalising these externalities with microalgae biofuels would be on the assumption that the technological developments would also improve the production efficiency and the resulting fuels would be a substitute in the longer-term.

5.5.3. Limitations and further research

The analysis undertaken in this study was limited to the information collected in the survey. This resulted in some shortcomings in terms of range of analyses. Hence, this section outlines how future adaptations of this study could be directed to collect new and more robust results to contribute to the literature.

This study focused on the marginal values of externalities from biofuel feedstock choice derived from individual consumers. The survey also included questions that asked respondents to ignore vehicles or fuel expenditures made for work or business purposes, focusing on personal use. This effectively excluded fuel sales and preferences from a business/commercial perspective, which represents a significant proportion of fuel sales in Australia. The reason for this was individuals vote explicitly for government representatives (and their accompanying policy decisions) rather than businesses. Hence, the marginal benefit values would be better represented by responses from individuals based on individual consumption preferences. However, this does present an opportunity in deriving the preferences for different biofuel feedstocks from business/commercial perspectives. These values could then be taken into account to determine a more aggregated value for the externalities across all fuel consumers, including from the commercial perspective. Given that businesses may not be focused on impacts outside of commercial objectives, the marginal values for the externalities would likely be much lower than those estimated in this study.

As previously mentioned, the high estimates for WTP, particularly for impacts to food prices, could be an indication of hypothetical bias resulting in inflated values from respondents. While the underdeveloped technologies in Australia make application of benchmarking difficult, there is the potential to introduce a 'cheap talk' treatment to a future study (Carlsson et al., 2005). In addition to highlighting the potential for responses to inflate values for the attributes, this script could also include reminders about budget constraints to ensure choices are made more realistically (Van Loo et al., 2011). This does increase complexity of the experiment and consideration should be then given in regards to corresponding cognitive burden on respondents.

It was mentioned in section 5.3.4.3 that respondents were assumed to exhibit symmetric preferences for gains and losses in each attribute. A potential extension to this study would be to investigate the potential for asymmetric preferences, similar to what was done by Hess et al. (2008) either using the same study sample or in another related study. Similarly, it was assumed that framing attribute levels by percentages would have a positive effect on the results. Future study on the use of absolute levels in comparison with these percentage-framed attributes, similar to Kragt and Bennett (2012) who found no significant difference in SP values.

A majority of respondents who were regular biofuel users had claimed their preference was due to the perception that biofuels were cheaper than their fossil fuel counterparts (Table 5.11). This did suggest some misperception of the costs of biofuels (by volume versus by energy content) and may have presented itself in the WTP for different attributes. This was not investigated here as the self-reporting of biofuel users showed some inconsistency (compared with Figure 5.9) and the sample size was small. Future study could investigate the likelihood of biofuel users who perceive the price difference as substantial having a higher WTP for the attributes using a larger sample size with more defined categories of biofuel users.

The modelling of ANA was relatively inconclusive and could have utilised more information or complex modelling. Accounting for individual serial SNA did not produce models with better fit, suggesting these may be misreported or that respondents did not systematically ignore the same attribute across their choices. The INA modelling indicated that respondents did not pay attention to all attributes (ignoring at least one) when making choices. However, the econometric methods undertaken again did not result in estimations of better fit or performance, although estimates seemed to suggest a disparity in WTP estimates.

Future research into ANA in this context could involve more rigorous ANA methods as applied in other studies. This includes task-specific ANA questions (i.e. asking SNA questions after each choice task) (Puckett & Hensher, 2008, 2009; Scarpa et al., 2010) or examining individual choices for inconsistencies (Sælensminde, 2002). The trade-offs of employing such methods are the high costs, including monetary costs for the analyst, and time and effort costs for the respondent. The latter could affect decision-making and resulting analysis. Hence, consideration should be given to these trade-offs when deciding on the most appropriate method of capturing ANA in future DCE studies.

5.6. Conclusion

The aim of this study was to determine the value of externalities of biofuels through consumer preferences.

The results showed that when faced with biofuels that have similar practical properties, consumers attach significant values on non-market externalities. These results are consequential when considering the likelihood of biofuels becoming an increasing proportion of the fuel market in Australia through mandates and other policy instruments. If biofuels were sold in mandated blends, the practical aspects of a biofuel (e.g. mileage, performance, access) would not represent a major issue when comparing the alternatives. Hence, the results illustrating the external benefit values of alternative biofuels should justify policy support specific to the development of alternative biofuels like those from microalgae.

The findings from this study add new information into the discussion of biofuel development and the efficiency of policy support. While less quantitative studies have consistently highlighted the external benefits of alternative biofuels, the results presented in this chapter have introduced monetary values to these benefits. The study also highlighted consumer preferences between the alternatives based on provision of these benefits. The findings will add to further discussion of the efficiency of policy support for biofuels.

Chapter 6. Current and potential policies for biofuels in Australia

6.1. Introduction

Biofuels are a key alternative for transport fuels given the threats to fossil fuel supply. This is due to the close substitutability with fossil fuels (Agarwal, 2007), thereby decreasing transition costs for consumers. In addition, biofuels have been touted as having numerous environmental benefits, which have been widely discussed in the literature (e.g. Coyle, 2007; Demirbas, 2008; Escobar et al., 2009; Hall & Scrase, 1998). The development and growth of these new industries can also have socioeconomic benefits, particularly to energy independence and fuel security (Banda, 2009; Gasparatos et al., 2013).

Biofuels have received significant policy support in some countries. This has allowed certain first-generation feedstocks, supply-chains, and technologies to develop relatively steadily, particularly if the policies encourage widespread production and use. Case studies in the USA and Brazil (Fulton et al., 2004; Goldemberg & Guardabassi, 2009; Sorda, Banse, & Kemfert, 2010) illustrate this significant role that policy can play in transitioning from fossil fuels, and supporting the development of biofuel industries.

There has been immense potential for biofuel use and development in Australia (Batten & O'Connell, 2007; O'Connell et al., 2007; Puri et al., 2012). However, there has been relatively limited uptake in terms of production and consumption (Bureau of Resources and Energy Economics, 2014c). While this can be attributed to a range of factors, a major cause is the comparably lower policy support that has stagnated the industry's development and may have also affected confidence among a proportion of the consumers; the latter evidenced in some of the responses to the survey outlined in Chapter 5 (see section 5.4.3). This in turn affects how policy is designed, given greater public support for maintaining the well-established status quo of less costly fossil fuel use and limited biofuel proliferation. This impediment to the development of conventional biofuels consequently affects the potential growth of alternative biofuels in Australia, which has been seen as a superior substitute in the longer-term for transport fuels (Chisti, 2007, 2008).

The previous quantitative studies in this thesis have introduced new information into the understanding of the biofuels market, particularly for the potential of third-generation biofuels. The findings illustrated how new biofuel alternatives from microalgae could become part of an integrated production system and where improvements in cultivation and processing could provide the greatest financial benefits (0). Assessing consumer preferences illustrated that in a biofuel (blend) market, consumers would have a higher willingness to pay for options that provided external benefits, particularly if they reduced the impacts to agriculture and food supply (**Error! Reference source not found.**). This is consequential in the choice of different biofuel feedstocks to develop through policy support in Australia.

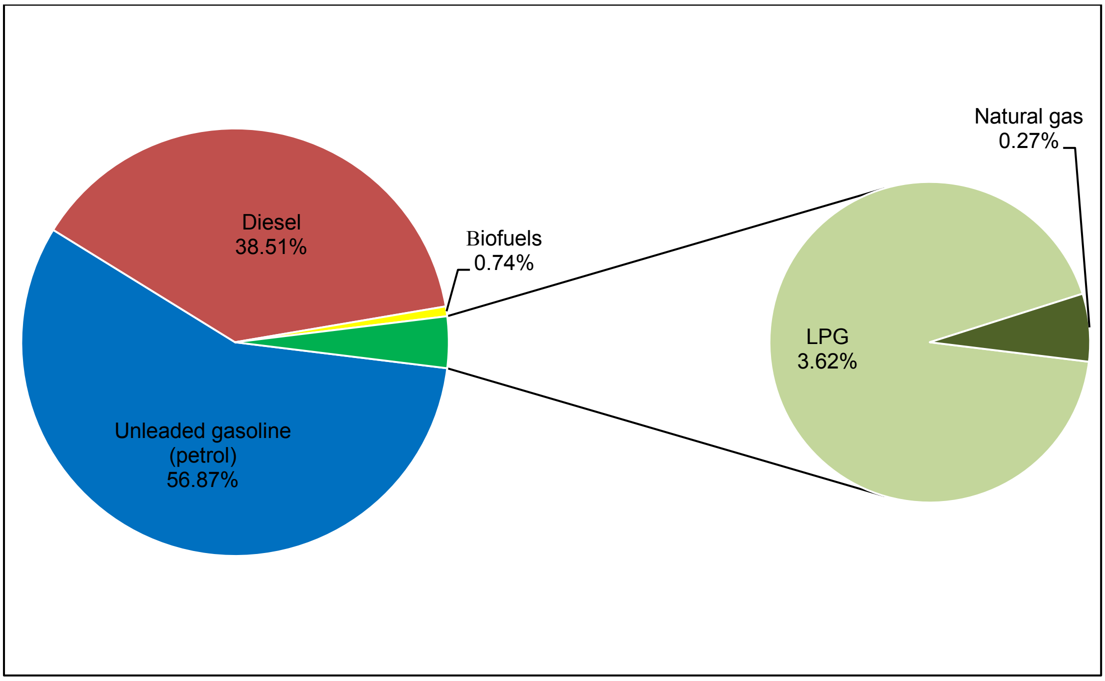
This main aim of this study was to determine if the current biofuel policy framework in Australia could be altered to develop microalgae biofuels. This aim was divided into two separate objectives: (1) identifying limitations in the current federal and state-based biofuel policy framework and (2) suggesting policy changes to further incentivize a transition to alternative biofuels based on findings from previous studies in this thesis and the existing literature.

The following sections outline the current transportation fuel use and the potential for increased biofuel consumption in Australia. Subsequently, federal and state-based policies are discussed with reference to statistics that demonstrate the resulting impacts of such policies on fuel consumption. Then, a discussion is developed on how the current policy framework dis-incentivizes growth of the biofuels industry and market in Australia, impeding development in longer-term alternatives. Finally, using the findings from the previous analyses and fundamental economic concepts, alternative policies are suggested, outlining the potential for government support of advanced biofuel technologies, both by state and nationally.

6.2. Transportation fuel use in Australia

Of the total energy consumed in Australia, transport energy is the largest proportion at almost 38% (excluding conversion activities across industries) (Bureau of Resources and Energy Economics, 2014a), about 74% attributed to road transport (Ball et al., 2014). The statistics also show that more than 95% of the fuel used in road transport is either petrol or diesel, with biofuels (including ethanol and biodiesel) being under 1% of fuel consumed (Figure 6.1).

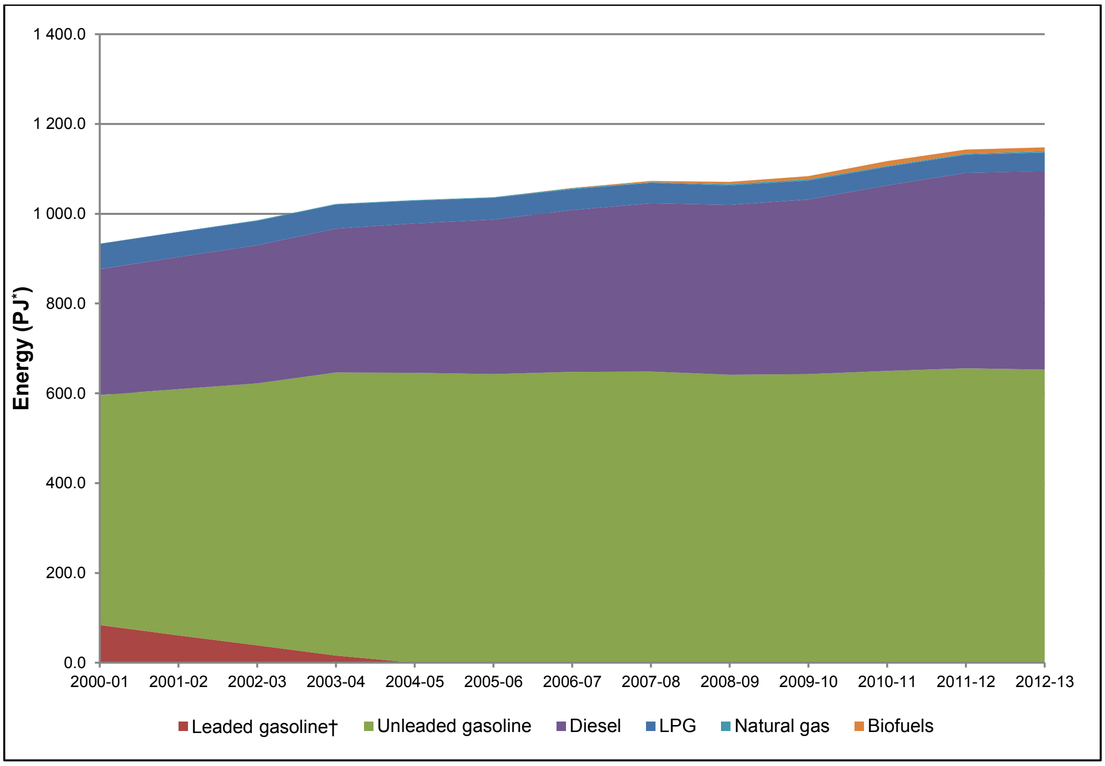
Figure 6.1: Australian energy consumption for road transport by fuel type (2012 - 2013).



Source: Bureau of Resources and Energy Economics (2014c Table F1).

The preference of fuel types for road transport has been relatively consistent over the past two decades. The only major change was the phasing out of leaded petrol[51] between 2000 to 2002, and replacement with Lead Replacement Petrol (LRP), which also steadily declined until mid-2004 (Bureau of Resources and Energy Economics, 2014a). This resulted in an upward shift of unleaded petrol consumers. The proportion of diesel consumers has also increased by about 8% across the decade with the proportion of petrol consumers decreasing slightly over the last five years. There has also been a slight increase in the use of natural gas and biofuels in transport but this is marginal compared to the proportion of petrol and diesel consumers (Figure 6.2).

Figure 6.2: Australian energy consumption for road transport by fuel type (2000 - 2013).



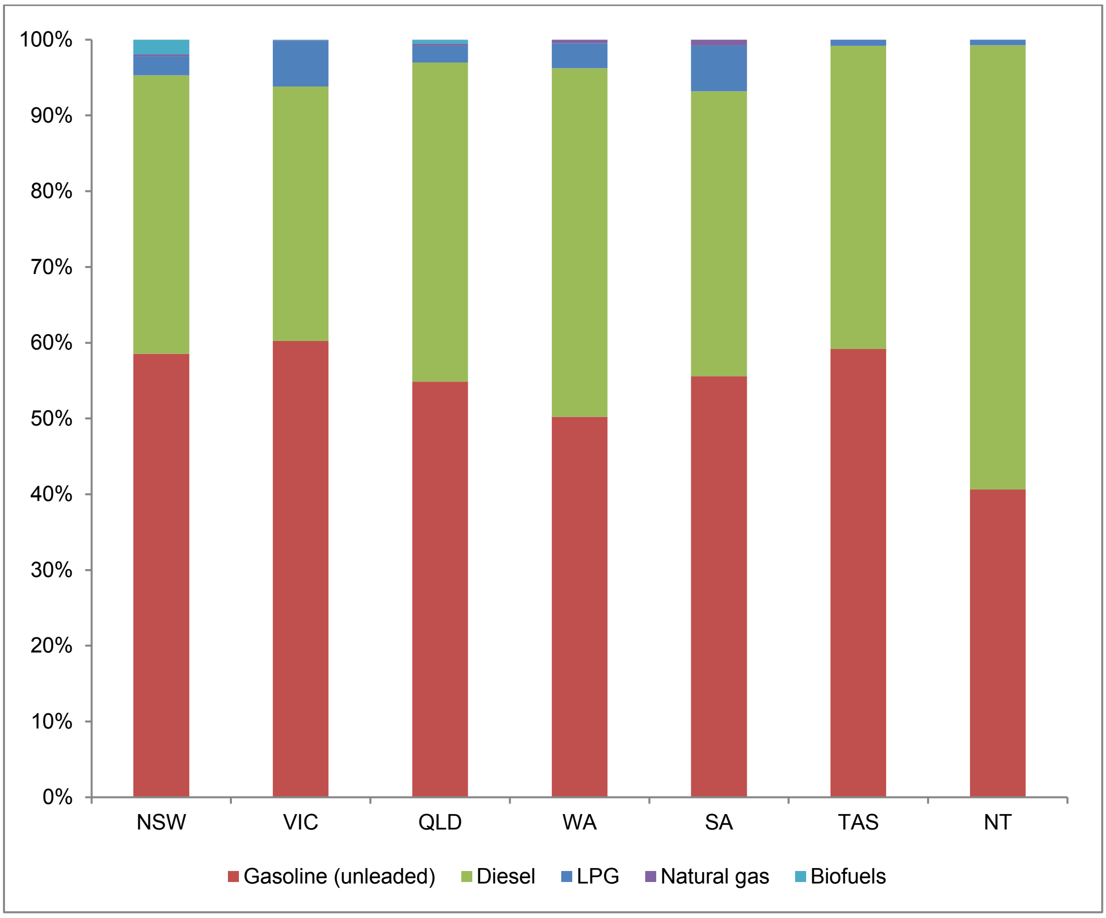
*1 petajoule (PJ) = 10^{15} J. †Lead gasoline includes Leaded Replacement Petrol (LRP).

Source: Bureau of Resources and Energy Economics (2014c Table F1).

[51] Petrol and gasoline are used interchangeably in this chapter.

The use of different transport fuels varies across the states, given different demand sources and fuel policies (the latter will be discussed further in this chapter). Diesel usage is about one-third of fuel consumption across most states except in Western Australia (WA) and the Nothern Territoty (NT), where it is closer to 50% and 60% respectively (Figure 6.3), due the greater mining industry and off-road usage (Ball et al., 2014). Biofuel consumption is highest in New South Wales (NSW), with the relevant blending mandates that were first introduced in 2007 (NSW Government, 2007). The bill to introduce a biofuel mandate in Queensland (QLD) was only passed at the end of 2015 to be implemented from the 1st January 2017 (The Parliment of Queensland, 2015); hence, the available data does not suggest any impact from policy yet. These policies will be detailed in the next section.

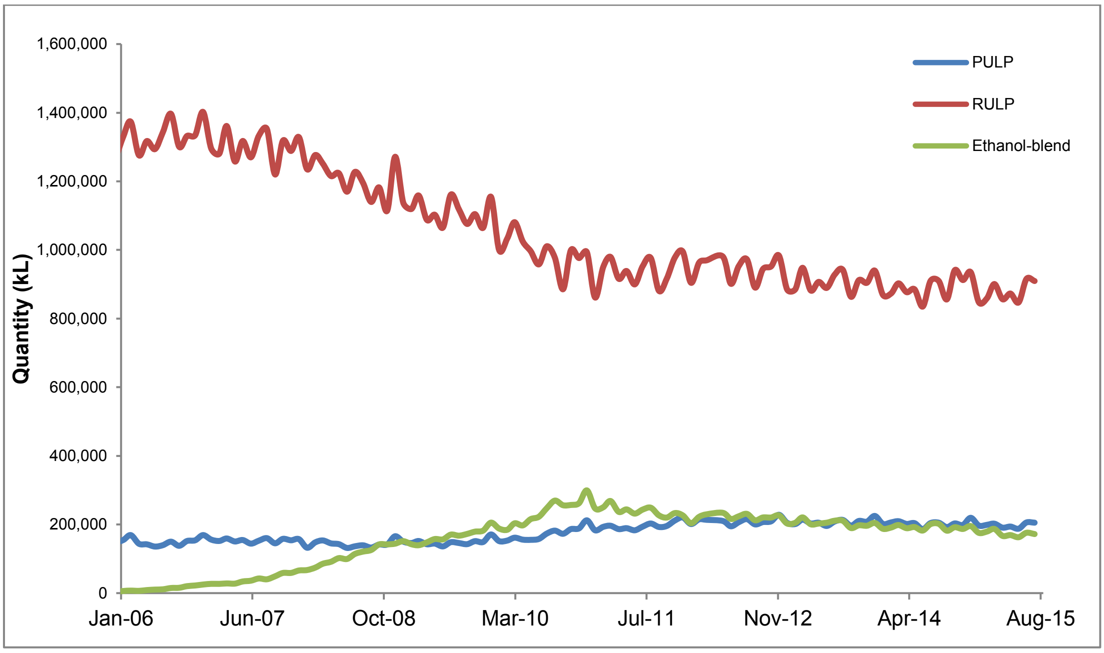
Figure 6.3: Australian energy consumption for road transport by fuel type and state‡ (2012-2013).



‡Data for ACT was unavailable.
Source: Bureau of Resources and Energy Economics (2014c Table F1).

Petrol is the most commonly used fuel for transport in Australia. Regular unleaded petrol (RULP) is favoured when comparing petrol alternatives across the country (Figure 6.4). However, there has been a decreasing trend of RULP sales in the past decade with an increasing trend of ethanol-blend sales, which can be largely attributed to the introduction and increasing ethanol mandate in NSW, compared to other states with relatively constant trends in ethanol-blend consumption[52]. Premium unleaded petrol (PULP) has remained relatively unchanged over the past decade on average across the country. There has been a slight decline in ethanol-blend consumption from 2011. Similar data were not available for biodiesel sales.

Figure 6.4: Monthly fuel sales in Australia (January 2006 - August 2015).



Source: Department of Industry Innovation and Science (n.d.Table 3B).

[52] Figures illustrating these trends can be seen in this chapter (Figure 6.5 for NSW and Figure 6.6 for QLD) and in Appendix L (for all other states).

6.3. Biofuels in Australia

Biofuel use in Australia can be regarded as being underutilised due to the current marginal usage despite significant opportunity to represent a greater proportion of fuel consumed. Despite federal legislation declaring ethanol as an excise-free fuel from 1921 (Australian Government, 1921), commercial-scale ethanol production only started in 1992 at the flour mills owned by grain processors, Manildra Group (Quirke, Steenblik, & Warner, 2008). A transition to other feedstocks[53] occurred as additional policy support was introduced, in particular molasses from sugar processing (L. Carson, 2014). Currently, ethanol is sold mostly in the E10 blend, the maximum percentage of ethanol in a blend permissible by law without requiring engine modifications[54] (Biofuels Taskforce, 2005). Biodiesel was initially produced at smaller scales in the early 2000s from cooking or vegetable oils. Production grew rapidly between 2006 and 2007 (Quirke et al., 2008), transitioning to tallow and oilseeds (e.g. canola) as feedstocks (L. Carson, 2014).

Currently, biofuels in Australia are only produced using first-generation feedstocks (and animal wastes for biodiesel) and related technologies. The majority of biofuel production plants are located in the east of the country (QLD, NSW, VIC) (L. Carson, 2014; Puri et al., 2012). A recent paper by Kosinkova et al. (2015a) has suggested the significant potential for biofuel production from new sources of feedstock across the country based on available first and second-generation feedstock, as well as potential for microalgae cultivation on less arable land, supporting findings from previous reports (Borowitzka et al., 2012; L. Carson, 2014; L.E.K. Consulting, 2011). The increase in production capacity of second and third-generation

[53] See Puri et al. (2012, Table 3) for a more comprehensive list of facilities, feedstocks, and capacities of biofuel production facilities in Australia.
[54] The alternative would be use of flexible fuel vehicles (FFVs), which are more common in the US, Brazil, and Europe. These vehicles allow use of blends with higher ethanol content (e.g. E85). FFVs are not currently available in the Australian market (Quirke et al., 2008).

biofuels in particular have been highlighted based on the opportunity costs of land and resource allocation across more coastal regions of the country.

6.3.1. Potential of microalgae biofuels in Australia

The potential for microalgae biofuel production specifically in Australia has attracted much attention among researchers (e.g. Institute of Molecular Bioscience, University of Queensland) and commercial producers (e.g. Aurora Algae prior to 2013, Muradel in 2014) given its availability of space and high solar energy exposure. Recent research by government agencies (Ball et al., 2014; Batten & O'Connell, 2007; L. Carson, 2014), private consultants (APAC Biofuel Consultants, 2013; L.E.K. Consulting, 2011), and academic researchers (Azad et al., 2015; Kosinkova et al., 2015a; Stephens et al., 2010) have all highlighted this potential for microalgae cultivation in Australia. Much of the excitement for microalgae biofuels in Australia has been centred on the potential for high cultivation volumes due to ideal climate conditions. However, there are currently no related commercial production facilities (APAC Biofuel Consultants, 2013) primarily due to the high biomass processing costs and low value of biofuel outputs compared to other high-value products currently in the market.

The techno-economic analysis presented earlier in this thesis (Chapter 3) did raise a potential production pathway for microalgae biofuels that yield financially feasible outcomes. This is through an integrated production system with complementary industries whereby input costs can be lowered through bio-fixation of waste streams. Also, the concurrent production of high-value products improves the feasibility of microalgae biofuel production, although it might not yield the most profitable outcome. Hence, policies to encourage potential investors and microalgae producers to invest in biofuel production would be essential for the development of this industry.

In addition to the benefits of bio-fixation, production and use of microalgae biofuels can provide additional economic benefits. As previously suggested, long-term dependence on first-generation biofuels may have impacts on food production and biodiversity through the competition for arable land and other agricultural resources (0). Microalgae biofuels reduce these impacts by its use of artificial cultivation environments and waste streams as sources of inputs. Hence, in a transition to increased biofuel use, consideration should be given to these external benefits given the non-market values attributed to them.

6.3.2. Biofuel policies and effects on fuel consumption

This section outlines a brief description of the major relevant policies surrounding biofuels in Australia, both nationally and within individual states. The impacts of these policies on consumption is illustrated where appropriate, using relevant statistics.

6.3.2.1. Federal biofuel policies

The excise tax rate for ethanol production in Australia from 2002 was similar to that of petrol at AUD$ 0.38143 per litre. However, domestic producers were afforded a grant, the Ethanol Production Grant (EPG), which directly offsets the excise (Bureau of Resources and Energy Economics, 2014b; Department of Industry, 2014). This grant was not afforded to ethanol imports and worked to protect domestic producers. From 2011 to 2015, a process of systematically phasing out the grant was introduced together with a lower excise rate for ethanol at AUD$ 0.125 per litre (Webb, 2014). Biodiesel was afforded a similar grants program, the Energy Grants (Cleaner Fuels) Scheme, which reimbursed the excise of domestically produced and imported biodiesel (Australian Government, 2004). However, this scheme was also ended on 1 July 2015 with providers allowed to register to claim until 30 June 2016 for sales up to 1 July 2015.

The taxation on both ethanol and biodiesel was altered based on an amendment passed in June 2015. From 1 July 2015, domestically produced ethanol and biodiesel will be taxed at a rate of zero. From the following year onwards, the excise rate of ethanol would then increase to 6.554% of the excise rate of petrol annually until July 2020, when the final rate of 32.77% is reached. Similarly, the excise rate of biodiesel increased annually from July 2016 to 3.333% of the excise rate of biodiesel until July 2030 when it reached to 50% (Parliament of Australia, 2015). Imported biofuels are not subject to this new taxation but are subject to customs duty that is equivalent to the excise tax on fossil fuels of AU$ 0.38143 per litre (Australian Government, 2014, p. 165).

6.3.2.2. State-based policies

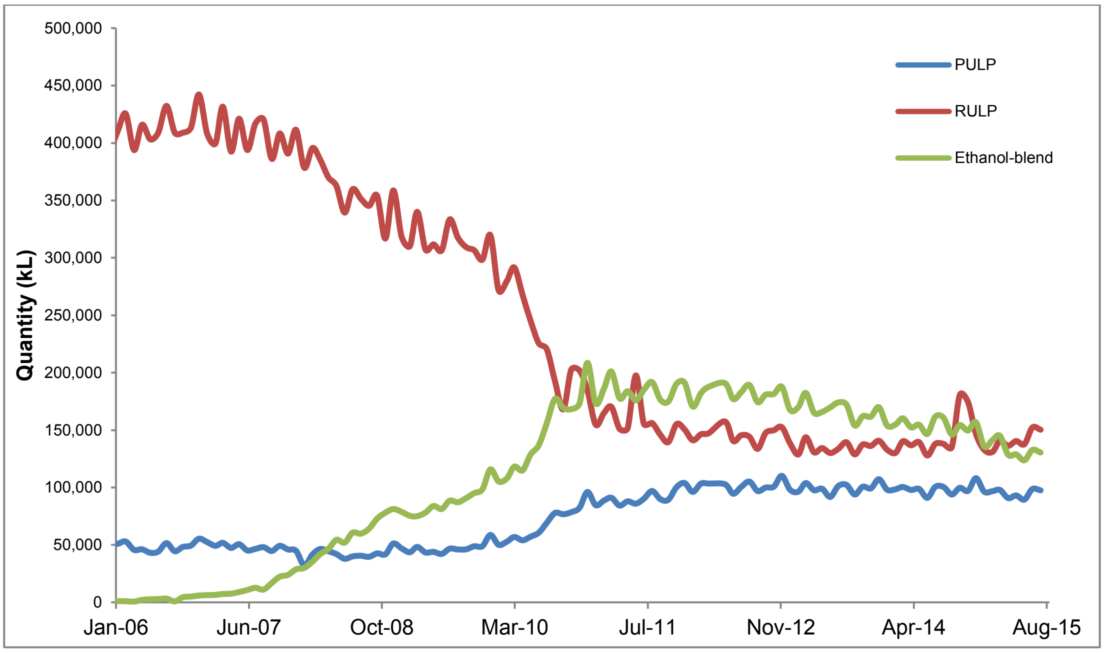
Currently only two out of the eight states have implemented biofuel mandates, New South Wales and Queensland. Although these policies include biodiesel, the majority of the discussion covers the impacts of the ethanol mandate due to the unavailability of similar data to represent biodiesel consumption.

New South Wales

NSW was the first state that introduced and continues to implement a minimum ethanol and biodiesel mandate, currently set by the state government at 6% for ethanol (originally at 2% in 2007) not including premium unleaded petrol (PULP), and 5% for biodiesel (also originally 2% in 2007) (NSW Government, 2007). These mandates require a minimum of fuel sales to be biofuels through increase in sales of blends e.g. E10, B5 (Quirke et al., 2008). Hence, if the ethanol mandate is at 6%, then E10 sales should account for (6% ÷10% =) 60% of related fuel sales.

The introduction and increase in mandates explains the fall of RULP sales and a consequential increase in ethanol blends (Department of Industry Innovation and Science, n.d.) (Figure 6.5). These mandates increase the availability of biofuel-blends and indirectly force consumers to substitute fossil fuels or blends. However, the data still shows that the proportion of biofuel sales to petrol is under the 6% target level; the data suggesting it to be closer to 3.8% (Department of Industry Innovation and Science, n.d.). PULP sales increased from 11.2% in 2007 to the 25.5% as of March 2015, suggesting some substitution of RULP with PULP rather than E10. PULP was left out of the mandate requirements on the assumption that certain vehicles require premium-grade fuels as per manufacturer recommendations. This was further substantiated through econometric analysis (Noel & Roach, 2016).

Figure 6.5: Monthly fuel sales in New South Wales (January 2006 - August 2015).

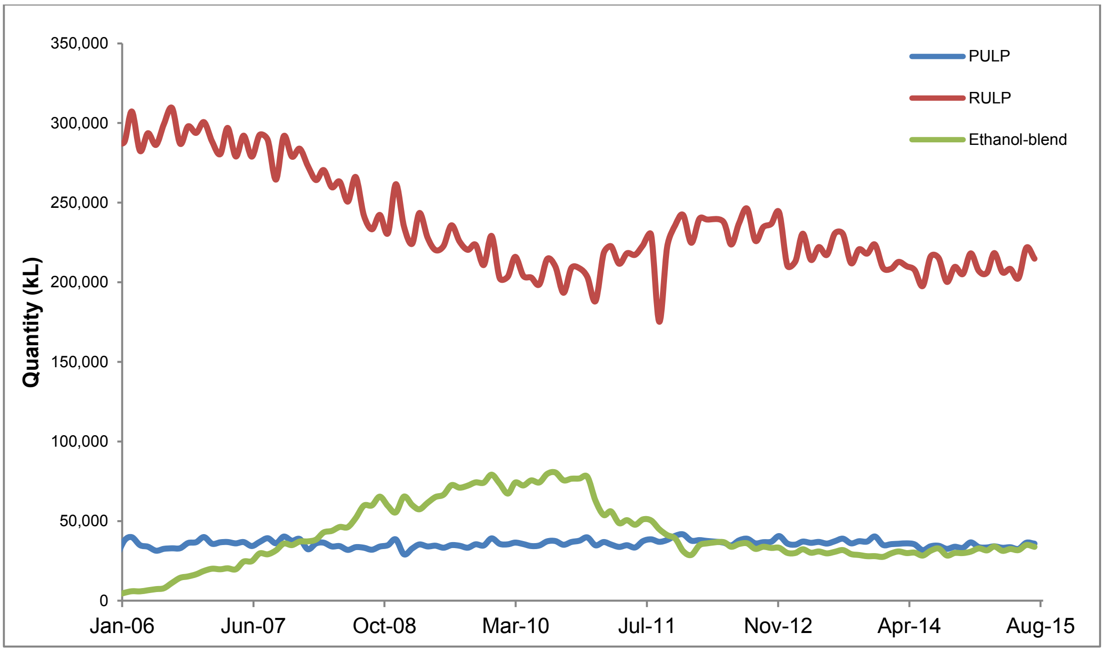


Source: Department of Industry Innovation and Science (n.d.Table 3B).

Queensland

The ethanol mandate progression in Queensland provides a good comparison with the progress made in NSW. Both states had relatively similar patterns of fuel consumption between RULP, PULP, and ethanol blends prior to 2007. The Queensland state government introduced a 5% ethanol mandate around the same time as NSW in 2006, to be implemented at the end of 2010. However, it was abandoned in October 2010. The impacts of the initial policy announcement and subsequent withdrawal can be inferred from the sales of the relevant fuels. Despite the increasing ethanol-blend consumption to over 20% up to late 2010, the state government's decision to abandon the mandate proposition was followed by a steady fall in ethanol blend consumption by 10% and a similar increase in RULP consumption (Department of Industry Innovation and Science, n.d.).

Figure 6.6: Monthly fuel sales in Queensland (January 2006 - August 2015).



Source: Department of Industry Innovation and Science (n.d.Table 3B).

More recently in late 2015, legislation was passed for a 3% ethanol mandate to be introduced from January 2017 for 18 months, before increasing to 4%. The biodiesel mandate, set at 0.5%, will also be introduced at the same time in 2017 (The Parliment of Queensland, 2015). The legislation outlines that the mandate would be applied to all fuels, including premium variants.

Victoria

In April 2007, the Victorian state government introduced a non-mandatory target for 2010 for 5% of fuels sold to be biofuels (both ethanol and biodiesel). However, after a parliamentary inquiry, a mandatory biofuel blending mandate was not advised due to perception of the shortcomings of such a decision, particularly with the lack of feedstock and its effects on food prices (Parliament of Victoria, 2008). This has led to the respective fuel market being heavily dominated by RULP at 87.5% (Department of Industry Innovation and Science, n.d., Table 3B).

Other states

Currently, no other states have implemented or have had public discussions on targets or mandates specifically for biofuels.

6.4. Limitations of current policies for biofuels

The lack of substantive policy support can be suggested as a major reason for the lack of biofuel uptake in Australia. In terms of national policy, the end of the tax-offsetting grants[55] suggests some level of inefficiency given the external costs of current fossil fuels (Eyre, Ozdemiroglu, Pearce, & Steele, 1997), and the external benefits that have been identified for biofuels (Goldemberg, 2007). However, the reasons for the increased taxation of biofuels were seemingly justified. Economic analysis had suggested that the economic benefits from the grants in terms of fuel security, employment, and emissions reductions did not match the high financial costs of the grants, distortions to the resource and energy markets (including competition with food demands), and costs of sustaining a reportedly unviable industry (Bureau of Resources and Energy Economics, 2014b).

[55] Although taxation of biofuels is at zero at the time grants were discontinued, the level of taxation on biofuels will increase annually as detailed previously. Hence, this discussion is about the ending of the grant and also the introduction of taxation on domestically produced biofuels.

However, the above findings were based on only policy support of first-generation biofuels. The report does suggest that support of first-generation technologies hinders growth of alternative energy sources including second-generation technologies (Bureau of Resources and Energy Economics, 2014b, p. 15). This assertion did not account for the high transition costs for producers and consumers if alternative technologies were to be developed without established policy support. Policy support for biofuels, even first-generation, can represent a major transitionary step for future fuel and energy alternatives (O'Connell et al., 2007). Given the potential for second and third-generation biofuels to be 'dropped in' existing blends and markets for biofuels (Regalbuto, 2009), a consistent federal policy support for biofuels might be able to transition consumers away from continual fossil fuel consumption, and simultaneously encourage investment and development in newer biofuel technologies.

Furthermore, the lack of additional state-based policies that support either production or consumption of biofuels leaves the potential market dis-incentivized from further developing. This includes the biofuel mandates in NSW that have failed to encourage biofuel consumption levels to meet the targets due to an inconsistency in the policy surrounding premium fuels, inferred through consumption statistics for PULP and ethanol-blends. Also, with potential for developing a range of feedstocks across the different states (Herr & Dunlop, 2011; Kosinkova et al., 2015a; Puri et al., 2012), the lack of substantial support in the development of these technologies have hampered any potential transition away from first-generation biofuels that have been plagued with economic costs.

Undoubtedly, policy has a significant influence on the growth of biofuel markets and industry, with the clear case study of Brazil. The initial provision of production subsidies, reduced duties, and tax exemption resulted in sugarcane-based ethanol as the most consumed fuel in the country (Sorda et al., 2010), with support for biodiesel being implemented more recently (Pousa, Santos, & Suarez, 2007). This is in contrast to the lack of an Australian biofuel policy framework, which has comparably stagnated growth of the industry, except for marginal developments in NSW. As a result, there is a lack of substantial supply chains for production, and reduced ease of access for consumers, the latter which is impeding further growth of the industry. More importantly, the lack of comprehensive biofuel policy support potentially hampers growth of second and third-generation biofuels, contrary to previous assertions (Bureau of Resources and Energy Economics, 2014b). This can leave society at lower welfare levels, particularly when considering the economic and transitionary costs of continual dependence on fossil fuels.

6.5. Policy recommendations

The literature has shown how policy is essential in determining the development of biofuel industries in a country (Gasparatos et al., 2013). While there may be suggestions of inefficiency of some policy instruments (de Gorter & Just, 2007, 2009; Grafton et al., 2010; Kalkuhl et al., 2013) and economic costs of first-generation biofuels in Australia (Bureau of Resources and Energy Economics, 2014b; Quirke et al., 2008), a substantive biofuel policy framework can potentially lead to a transition to more sustainable and economically beneficial alternatives. The following section will outline key recommendations for a biofuel policy framework in Australia.

The recommendations below are based on the security of supply and positive externalities of biofuels justifying the need for policy intervention. The two key areas these recommendations will address are: (1) the development of diversified biofuel technologies, and (2) the potential misinformation among consumers.

6.5.1. Development of diversified biofuel technologies

Currently, biofuels in Australia are only derived from first-generation feedstocks. The literature as covered in Chapter 2 has consistently identified potential issues with these feedstocks, from technological and economic perspectives. In particular, first-generation biofuels raise opportunity costs for food-crop and agricultural resource re-allocation, especially with potential increased demand (see section 2.2.6). These can result in the lack of further policy support (Bureau of Resources and Energy Economics, 2014b; Quirke et al., 2008). Consequently, the market is left dependent on petrol and diesel, which raises further economic issues particularly in terms of long-term supply.

Based on suggestions by Kosinkova et al. (2015a), development of a diversified biofuel feedstock supply is required to meet potential increase in biofuel demands and reduce potential economic costs. This includes developing specific conventional feedstocks, where abundant, and investing in alternative feedstocks in areas where ideal conditions and/or complementary industries are located. In terms of second-generation feedstocks, there is substantial opportunity for development on the east coast of Australia where there is an abundant supply of agricultural and forestry residues/wastes (L. Carson, 2014; Covey, Rainey, & Shore, 2006; Herr & Dunlop, 2011). However, investing in second-generation crops cultivated specifically for biofuels raises the opportunity cost for resource allocation for food production.

In terms of microalgae biofuels, the results from Chapter 3 have shown the benefits of microalgae production as part of an integrated production system with complementary industries. This also provides non-market bio-fixation benefits of the waste effluents from complementary industries. Studies focusing on climate and land conditions have identified parts of WA and NT as ideal (Borowitzka et al., 2012; L.E.K. Consulting, 2011). However, based on locations of complementary aquaculture industries, there is also the potential for production to be located around major producers in QLD and NSW. This is due to the potential availability of high-nutrient content wastewater from these industries to be used as microalgae growth mediums. Additionally, studies have indicated the potential for microalgae cultivation with municipal and other industrial sources of wastewater (Andersson, Broberg, & Hackl, 2011; Pittman et al., 2011; Woertz et al., 2009), which could suggest production across various regions of Australia with high population or industrial density. Nevertheless, consideration must be given to the trade-offs of such facilities given limited space and availability of ideal climate conditions to realise maximum growth rates (Kosinkova et al., 2015a).

Presently, these second and third-generation feedstock options are largely impeded by high costs (Davis et al., 2011; Demirbas, 2008; Hill et al., 2006; Norsker et al., 2011). These costs accrue from feedstock collection, transport, and biofuel production. Considering that second and third-generation biofuels are not commercially produced in Australia, this would suggest issues with underdeveloped infant technologies and production systems. Additionally, the literature has rarely shown practical use beyond experimental testing (e.g. Haseeb, Fazal, Jahirul, & Masjuki, 2011; Xue et al., 2011). With the intention to use them as ‘drop-in’ fuels, significant research and development (R&D) is required for these biofuels to be regarded as practical substitutes not only for first-generation biofuels but also fossil-based fuels.

The findings from Chapter 5 have demonstrated the significant non-market values of the external benefits, particularly the impacts to agricultural resources and biodiversity. Thus, policy intervention is justifiable given the existing market failure. Public investment to yield a socially efficient outcome is inferable based on economic fundamentals (Hubbard et al., 2013). State-based initiatives to improve the feedstock supply would encourage the development of more efficient supply chains across a diverse feedstock network. This includes facilitating the reallocation of agricultural and forest residues for biomass conversion of second-generation biofuels. In terms of microalgae biofuels, federal and/or state-based initiatives could be introduced for existing industries to integrate microalgae production facilities or to redesign wastewater treatment systems to benefit from the potential synergy with microalgae production.

Additionally, this policy support could include federal investment in the technological R&D of production and conversion systems for newer feedstocks (second and third-generation). In particular, it is imperative to support the development of drop-in biofuels that perform similarly if not in a superior way to petrol and diesel (including premium variants), at a comparable price. This also applies to ensuring practical use in a wider range on engine specifications and manufacturers, particularly in existing vehicles, which reduces the proportion of vehicles not compatible with biofuels (and blends). The technical literature on this aspect of biofuels suggests that current biofuels exhibit lower power and mileage due to lower energy content and higher viscosity (Xue et al., 2011). However, there continues to be advances in the refining of biofuels and understanding of chemical properties of drop-in biofuels (Bergthorson & Thomson, 2015). Increased federal and state government support of R&D efforts in this field could potentially drive the technological progress.

These policy tools can allow for the internalisation of the positive externalities of biofuels. By investing in the key areas identified above, the policy can effectively transition transport fuel production to a sustainable alternative but at lower private transition costs compared to other forms of transport energy (e.g. electric, LPG/CNG). The transition then ensures that society benefits from the direct external benefits, including decreased emissions, and lower impacts to agriculture and biodiversity. In addition, it allows for the growth of a long-term industry that can sustain fuel demands, and also employment and economic growth.

6.5.2. Misinformation among consumers

The other aspect that requires policy attention is to reduce the occurrence of misinformation among consumers. The survey results in Chapter 5 have shown common reasons consumers did not purchase biofuel-blends regularly were the perceptions that their vehicles were not suited or recommended for biofuels (with comments adding that the blends would likely cause damage to their engines) and that they would experience lower performance and/or mileage (see Table 5.12). These (mis)perceptions are consistent with the existing literature (Van de Velde et al., 2009). It was also found that this 'aversion' caused by the negative perception for biofuel-blends had resulted in consumers in NSW switching to premium fuels rather than consuming the ethanol-blends (Noel & Roach, 2016).

Although some studies substantiate these claims (Haseeb et al., 2011), such studies have focused on high percentage blends (50% and over). Lower percentage blends (about 20%) have been suggested to have no impact on engines, whilst improving performance (Agarwal, 2007). In addition, current retail blends (like E10 or B5) have been said to have negligible impacts on performance (Xue et al., 2011). These findings also justify an increasing number of manufacturers extending warranty on engines from commercial (low percentage) biofuel-blend use (Haseeb et al., 2011). Studies have also found an increasing percentage of vehicles compatible with current commercial blends (Independent Pricing and Regulatory Tribunal, 2012; Noel & Roach, 2016). The practical aspects of the fuels have been regarded as more important in quantitative (Dagsvik et al., 2002; G. O. Ewing & Sarigöllü, 2000; Fimereli & Mourato, 2009; Giraldo et al., 2010; Khachatryan et al., 2011) and qualitative literature (Johnson, Edgar, & Edgar, 2013; Van de Velde et al., 2009) compared to the external benefits. Hence, with the clear evidence of the direct substitutability of current commercial biofuel-blends (Agarwal, 2007), it can be inferred that that some level of information failure exists among consumers regarding the practical aspects of biofuel-blends, which is another indicator of market failure.

Improvements to higher percentage blends and development of technologies for pure biofuels are required in the long run. However, low percentage biofuel-blends represent a key transitionary step for all stakeholders in the transport fuel market. In addition to allowing the establishment of defined production systems, it allows consumers to substitute fossil-based transport fuel purchases at a lower opportunity costs. This can cause a subsequent shift in the transport fuel market, which would encourage further investment in biofuels from producers, retailers, and engine manufacturers. Therefore, if consumers have misinformation about the substitutability of biofuel-blends, this transition away from fossil fuels is impeded, affecting potential welfare for society.

Hence, policy intervention is required to correct this market failure. The practical implications of current biofuel-blend use on engine performance and maintenance require clearer communication to consumers. This can be in the form of marketing campaigns, and more practically, in reducing misinformation spread from manufacturers, retailers, and mechanics. Such measures ensure that consumers receive full information about these impacts of biofuel-blend use, and make the most socially efficient choices. With results from Chapter 5 adding to the literature on consumer preference for external benefits of transport fuel use, this would likely result in a greater acceptance for biofuel-blends.

Also, this potential change in consumer choice may alter preferences as consumers become more aware of the external benefits of biofuels. There may be a greater realisation of the longer-term benefits of biofuels, stimulating a greater demand for current blends from producers and retailers. Also, consumers may consequently demand less fossil fuel use, forcing fuel producers and manufacturers to invest more in R&D of higher percentage blends or pure biofuels for use in transport.

6.6. Conclusion

The aim of this chapter was to identify current biofuel policies in Australia and suggest alternative biofuel policies in Australia.

A review of the current biofuel policies in Australia identified that there was a substantial lack of policy instruments supporting biofuel production and use. This includes the introduction of taxation of biofuels and the lack of further state-based initiatives. While studies have indicated the potential for biofuels in Australia and the benefits from conventional and alternative biofuels over fossil fuels, the lack of substantive federal and state-based policy support suggests some level of societal inefficiency. The suggestions outlined in the second part of this chapter identify key areas in which policy intervention could be introduced to achieve a socially optimal outcome in the given context.

Chapter 7. Conclusions

7.1. Introduction

The potential of microalgae as a feedstock for biofuel production has received increasing attention. The various external benefits of its use have drawn much interest across academic (Darzins et al., 2010; Davis et al., 2011) and commercial research (APAC Biofuel Consultants, 2013). However, with its current processing technology in relative infancy, it remains financially unfeasible. As such, much of the research in this field has been focused on the science and engineering aspects of production to improve feasibility (e.g. Alabi et al., 2009; Lundquist et al., 2010; Taylor et al., 2013). Nevertheless, with conventional biofuels unable to attain more than a marginal proportion of transport fuel usage in Australia, the prospects of microalgae biofuels would seem long-term at best.

The breadth of literature on microalgae biofuels fails to highlight how policy plays an essential role in the uptake of a new technology in transport. This has been especially evident with the transitions to biofuels in USA, Brazil, and parts of the EU. Therefore, the feasibility of microalgae biofuels requires analysis on a broader economic perspective to determine the potential financial feasibility and economic efficiency in delivering greater welfare for society. Although various potential opportunities and benefits of the technology have been discussed in more qualitative literature (e.g. Chisti, 2007, 2008), there has not been any substantive economic analysis to address these gaps.

The research undertaken in this thesis was aimed at addressing the economic costs and benefits of microalgae biofuels from both production and consumption, and how policy could be re-framed in the context of the Australian biofuel market.

This chapter summarizes the work undertaken for this dissertation. Firstly, the aims and objectives of this dissertation will be presented. Then, a systematic description of the findings will be put forward, followed by a discussion of the limitations and opportunities for further research. This chapter is then concluded with overall comments on the potential for the potential of microalgae biofuels.

7.2. Research aims and objectives

In this dissertation, the main objective was to increase the understanding of the economic benefits and costs of microalgae biofuels, and suggest related policy recommendations in Australia. This broad aim was further divided into the following research questions:

1. Based on the current knowledge of biofuels, what are the economic benefits of microalgae biofuels to warrant their consideration as a long-term transport fuel alternative?
2. How can the positive externalities from production and a multi-output system improve the financial feasibility of microalgae biodiesel?
3. How sensitive are the financial parameters of microalgae biodiesel production to fluctuation in input and output prices?
4. What are the non-market values of the externalities from biofuel consumption?
5. Given the findings from the previous studies, what are the key areas that policy should address in supporting development of microalgae biofuels?

The studies undertaken introduce broader economic information into the discussion on this new fuel technology. In particular, this thesis delves into the externalities surrounding microalgae biofuel production and consumption. In addition, the findings help to illustrate the potential of the industry from both private and public investment perspectives.

7.3. Results and contributions

In order to meet the objective of this thesis, the respective studies were designed to address each research question systematically. The results and discussions presented in this section are summaries of each study, and are outlined at the end of this chapter in Table 7.1.

7.3.1. Review of the potential of microalgae biofuels over conventional biofuels.

The first study in this thesis was a comprehensive review of the literature surrounding conventional and alternative biofuels. The aim of this study was to identify the economic benefits of microalgae biofuels over their conventional predecessors. Also, aspects identified in this study informed the development and direction of subsequent studies in this thesis.

Firstly, the review revealed that despite receiving much attention and policy support, the external benefits of conventional biofuels might have been overstated. In particular, the competition for land and other agricultural resources raises significant costs in terms of loss of carbon sinks, decline in biodiversity, and potential increase in food prices. Increase in dependence on conventional biofuels would likely further exacerbate these issues.

Conversely, use of microalgae as a feedstock for biofuel production has been shown to potentially result in numerous economic benefits. The cultivation in artificial environments decreases the pressure on scarce agricultural resources and need for clearing of diverse terrestrial ecosystems. In addition, the ability for the biomass to thrive in carbon and nitrogen-rich environments allows for bio-fixation benefits of industrial waste effluents.

These include carbon dioxide from power plants and nitrogen-rich wastewater from municipal or aquaculture sources.

However, the feasibility of microalgae biofuels has been impeded by the high production costs. Studies have identified the high capital costs of biomass conversion (e.g. transesterification) equipment and low value of biofuels to be major hurdles. This has led to the majority of microalgae production to focus on non-biofuel outputs (e.g. fertilisers, human nutrition compounds, livestock/aquaculture feed). Some studies have identified the potential to utilise the biomass for production of these higher-value outputs as co/by-products to biofuels, thereby achieving financial feasibility.

The review identified the importance of policy in the development of conventional biofuels. This is especially true in countries like Brazil, USA, and parts of the EU. Policy intervention supports advancement in the production and growth in the market demand through various measures including tax credits, subsidies, and blending mandates. More importantly, policy intervention ensures a greater efficiency by accounting for external costs and benefits. However, the efficiency of policy support for conventional biofuels is debatable given the numerous external costs that were identified in this review. Also, with biofuels representing a closer substitute for liquid fossil fuels in transport, the external benefits of microalgae biofuels compared to conventional alternatives could justify targeted policy support.

7.3.2. Techno-economic analysis of microalgae biodiesel production

The second study presented an extension to the typical techno-economic analysis already popular in the literature on microalgae biofuels. In this study, two major aspects were added: (1) a multi-output pathway and (2) integrated production system. The former involved designing a mass balance framework that allowed for the cultivated biomass to be allocated to three outputs: biodiesel (from transesterification of lipids), agricultural fertilisers, and aquaculture feed. The proportions of biomass could be adjusted for both primary allocation (to all three outputs) and residual allocation (to fertiliser and feed). Although much of the qualitative literature has highlighted this as a potential option for achieving financially feasible biofuel production, this study represents the first attempt for microalgae in the literature. For the latter, an assumption was made that the growth medium of wastewater from a complementary industry was utilised, already containing an amount of nitrogen and phosphorus. This would mimic the bio-fixation of wastewater touted heavily in the qualitative literature.

A net present value (NPV) analysis was conducted with various growth parameters and base allocation proportions of biomass. The analysis found that feasibility of biodiesel production was heavily dependent on the production of higher value co-products. This is due to the high capital costs of transesterification equipment and significant annual capital maintenance costs.

A sensitivity analysis was also carried out in this study across a number of engineering and economic parameters. The results here illustrated that developments in the growth rate have the highest potential impact on NPV of the production system. Aside from this, a largely expected finding was the negative relationship between an increasing proportion of biomass allocated to biodiesel and the NPV. This is again due to the high capital and operating costs of the process and low return from biodiesel revenues. This finding is consistent with real-world examples of microalgae producers focusing production of more high-value (non-energy) products rather than energy products. The accompanying switch value analysis outlined representative levels of a number of parameters affecting the feasibility of the system in terms of NPV.

While this study reaffirmed perceptions that high NPVs are achieved through focusing on high-value non-energy outputs, it also suggested how this could be used to achieve financially feasible production of biodiesel. Producing biodiesel and other output products concurrently would offset the higher financial costs of biodiesel production. In addition, the benefit from bio-fixation of nutrient-rich wastewater adds an external benefit to the system, which could be used to justify support from complementary industries (that have costly waste effluents) and from policy. The study undertaken provides an indication of the benefits of developing integrated industrial systems that can benefit numerous stakeholders.

7.3.3. Techno-economic profit function

The third study addressed the impact of price fluctuations on potential profitability by deriving a profit function using simulations of production scenarios. This represented a novel use of simulations of a techno-economic model (from the previous study). The results indicate that annual profitability was largely revenue driven and as such, annual profitability was achievable. However, the choice of output mix had significant impacts on both the NPV and levels of profit. Fertiliser and feed outputs were expectedly found to have greater positive impact on profits compared to biodiesel.

Expectedly, the analysis found that as energy and maintenance (for capital input) prices increased, a profit maximising producer would substitute biodiesel production for fertiliser or feed. This again reflects the comparably lower revenues and higher costs of increased biodiesel allocations and the financial returns from the high-value outputs outweighing the increased costs of biomass drying.

Most interestingly, the profit function estimation highlighted the positive relationship between the interaction of growth rates and biodiesel price with profits; implying that an increase in growth rates would improve the profitability of biodiesel production from microalgae.

The use of this methodology represents a major contribution to the TEA. In particular, it highlights the potential analysis that can be undertaken when faced with hypothetical production models and alternative use of stochastic simulations with a multiple outputs.

7.3.4. Consumer preferences for biofuels

The fourth study presented a DCE to assess the consumer preferences for externalities of biofuel consumption. This involved a survey that was undertaken on a sample of respondents that were representative of the Australian population and fuel consumers. Although similar studies have been attempted with biofuels previously, this study attempted to isolate the non-market values for the external benefits only, not accounting for practical aspects of fuels that have dominated the other studies in this context.

Initial results indicated that consumers had a high WTP for the external benefits assessed, particularly the impact of biofuel on food prices. Consumers were found to be willing to pay more than double the fuel price to avoid a marginal 10% increase in their food price. The impacts of biofuel consumption on net emissions and biodiversity were also considerable. Respondents were found to value the origin/source country of the biofuel the least, but still exhibited a highly significant and considerable WTP estimate.

Further estimations of more complex modelling revealed the presence of possible heterogeneity within the sample. For example, respondents from WA were found to have a much higher WTP values for the attributes, even compared to states that have had policy (discussions) around biofuels (i.e. NSW and QLD). Additionally, income-based partitioning indicated that the lowest reported income group had the highest WTP across all attributes, contradicting assumptions of the positive relationship between income and marginal WTP.

An investigation into ANA suggested that while it was likely that respondents ignored at least one attribute in their decision-making, it was difficult to ascertain which attributes were ignored through SNA methods. More complex econometric methods were used to determine the presence of INA, which affirmed that respondents likely did not consider all attributes when making their choices. The source of the biofuel was found to have the highest possible occurrence of INA, affecting the marginal WTP estimate for this attribute.

Using the estimates derived in this study and findings from the review in 0, it was asserted that third-generation biofuels, like microalgae biofuels, had the highest non-market value among the three generations of biofuels. This was primarily due to the low impacts on food prices and net emissions compared to first and second-generation biofuels. Hence, if policy and technological development were to result in similar practical aspects of the biofuels, third-generation alternatives would warrant the greatest public support due to the high-valued social benefits of the biofuel feedstock.

7.3.5. Current and potential policies for biofuels in Australia

This final study investigated the biofuel policy framework in Australia. A brief review of the federal and state policies identified shortcomings, particularly with the lack of support of biofuels due to the negative externalities of first-generation biofuels. This chapter highlighted the inefficiency of this policy direction. In particular, given the economic benefits of second and third-generation biofuels, policy intervention would be required as part of a transition away from fossil fuels. Two broad areas were identified addressing the development of diversified biofuel technologies and addressing consumer misinformation. The rationale for each was detailed, together with a number of policy suggestions. Given the importance of policy in the development of biofuels, the establishment of a clear framework in Australia can potentially allow for a longer-term transition to alternative biofuels like microalgae.

7.4. Limitations and further research

As previously mentioned, the studies undertaken in this thesis all represent new contributions to the literature on microalgae biofuels and even to biofuels more generally. However, there were limitations to the research presented in this thesis, both specifically to each study and more broadly to the context. Although limitations to each quantitative study were covered in greater detail in each of the preceding chapters, this section will briefly reiterate the main limitations of each quantitative study.

A number of limitations with the TEA approach were identified, which were classified into two broad categories. In terms of the engineering perspective, this study could be further refined through use of engineering-specific modelling software, incorporating a greater range of output products with different processing, and more accurate production parameters. In terms of economics, the study could be extended to incorporate risk and policy analyses. While the former has been attempted for single output systems, the production of multiple outputs would add additional complexity.

The limitations with the techno-economic model affected the estimation of the profit function in Chapter 4. The results had indicated some issues in estimating the elasticities of the outputs. This was attributed to the assumption made that affected the revenue shares of biodiesel. Further use of the profit function would benefit from more accurate production data, which would involve more practical parameters. Developments in the biodiesel production process that improve its cost efficiency could allow for more evenly distributed revenue shares, resulting in a better indication of the impacts of the output mix to profitability.

The DCE study was subject to issues with ANA. While effort was made to capture and model its effects, the results were somewhat inconclusive. In particular, there was the possibility that respondents may have ignored difference attributes in each choice set. It was suggested that incorporating more rigorous ANA surveying would improve the results, but consideration was required regarding the additional costs from these efforts.

7.5. Final conclusions

Biofuels are a potential key substitute in the transport fuel market. However, economic costs that plague conventional biofuel feedstocks suggest the need for developing alternative feedstocks like microalgae. Policy has been instrumental in the development of biofuel industries and markets. However, the literature on microalgae biofuels has been concentrated in disciplines that do not address the economic costs and benefits of the fuel, leaving policy intervention in this technology relatively scarce.

The purpose of this dissertation was to introduce a broader economic scope to the literature on microalgae biofuels. A consistent theme across the findings was the immense potential of the technology from private industry and societal welfare perspectives. However, like any new/infant technology, policy intervention would be required to ensure realisation of these benefits. The suggested policy recommendations capture key areas for improvement in the

Australian biofuel policy framework. Further developments in the production and use of microalgae biofuels are required. However, the economic research undertaken illustrates a broader approach to evaluating the technologies that could benefit development and justify its long-term substitution into the transport fuel market in Australia.

Table 7.1: Summary of findings from individual research aims.

Aim	Aim 1	Aim 2	Aim 3	Aim 4	Aim 5
Overview of findings	Limitations of conventional biofuels in three key areas: net carbon emissions, biodiversity, crop/resource allocation. Microalgae biofuels avoid similar limitations. Microalgae production benefits through bio-fixation and production of multiple outputs. Microalgae technologies hindered by high costs. Policy identified as key determinant to development of biofuel technologies.	Integration of microalgae production with waste producing industries reduced operating costs. Production of multiple outputs essential to achieving positive NPV. NPV most sensitive to growth rate.	Substitution effect between biodiesel production with feed and fertilizer given increased energy and capital maintenance costs. Positive relationship between interaction term of biodiesel price and growth rate with profits.	High marginal values observed across all attributes, particularly for impacts of biofuel production on food price. Lowest income groups shown to have highest willingness to pay across all attributes.	Inefficiency of federal biofuel-related policies in Australia. Mandate policies in NSW found to be ineffective due to loopholes. Identified key areas for policy improvements based on findings from Aims 1-4.
Research implications	Identified key research gaps in microalgae biofuel research.	Novel use of incorporating multiple output production. Methodology depicts feasibility of multi-output system integrated with complementary industries that benefit from bio-fixation e.g. aquaculture.	Introduction of profit function estimation using techno-economic production simulations. Illustrates importance of output mix on profitability.	Derivation of economic values for externalities of different biofuel feedstocks.	
Policy implications	Highlighted key economic issues to consider in increasing policy support of biofuel development.	Production of high-value outputs could justify private investment in short-term. Public investment in research and development of growth and conversion technologies required to justify greater policy support of microalgae biodiesel production.	Public investment in research and development of growth rate can improve profitability of biodiesel production in longer-term. Higher-value outputs may justify investment in cultivation infrastructure while developments in biofuel technologies occur.	Third-generation (microalgae) biofuels found to have highest social benefit values among biofuel feedstock choices. Justifies policy involvement in development of technologies for long-term substitution	Policy investment in diversified biofuel technologies and addressing consumer misinformation required for transition away from fossil fuels.

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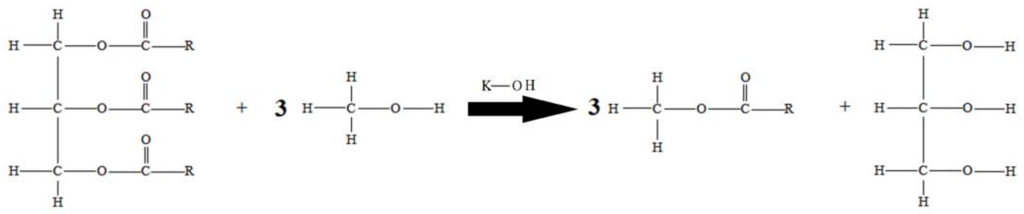
Appendices

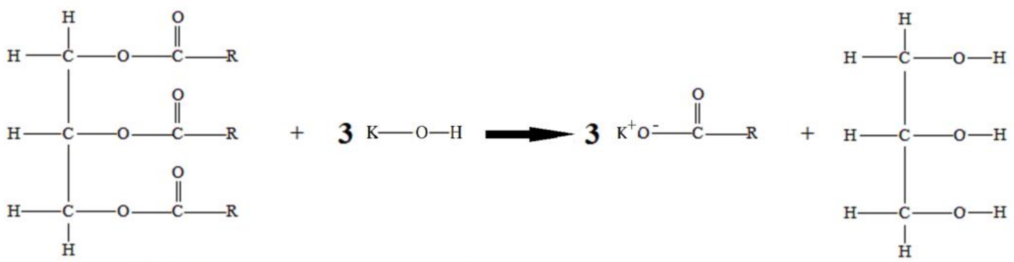
Appendix A

This first section presents the chemical equations used to model the mass stoichiometry of the reactions in the transesterification process. The first equation depicts the conversion of TAGs to FAME by transesterification with methanol using potassium hydroxide as a catalyst.



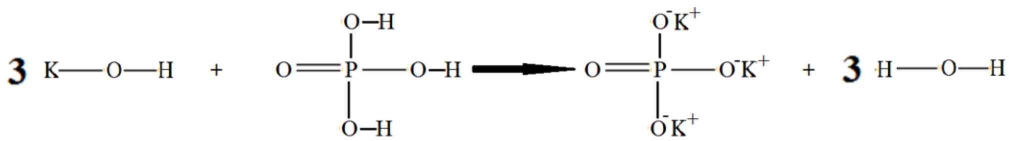
Triaclyglyceride (TAG) **Methanol** **Fatty acid methyl esters (FAME)** **Glycerol**

The unintended reaction (saponification) between FAME and the potassium hydroxide catalyst can occur to form a potassium soap and unrecoverable glycerol. This results in a loss in efficiency of the transesterification process.



Triaclyglyceride (TAG) **Potassium hydroxide** **Soap** **Glycerol**

Finally, excess potassium hydroxide that did not react with the TAGs is neutralised with phosphoric acid to produce a salt and water.



Potassium hydroxide **Phosphoric acid** **Tri-potassium phosphate** **Water**

Appendix B

The following figures illustrate the mass balance framework for the techno-economic model used in Chapter 3. The conceptual framework of the mass flows is shown in Figure B.1. The Microsoft Excel spread sheet frameworks of the baseline scenario and the respective mass flows is shown in Figure B.2, Figure B.3, and Figure B.4.

Figure B.1: Framework of mass flows in multi-output techno-economic model.

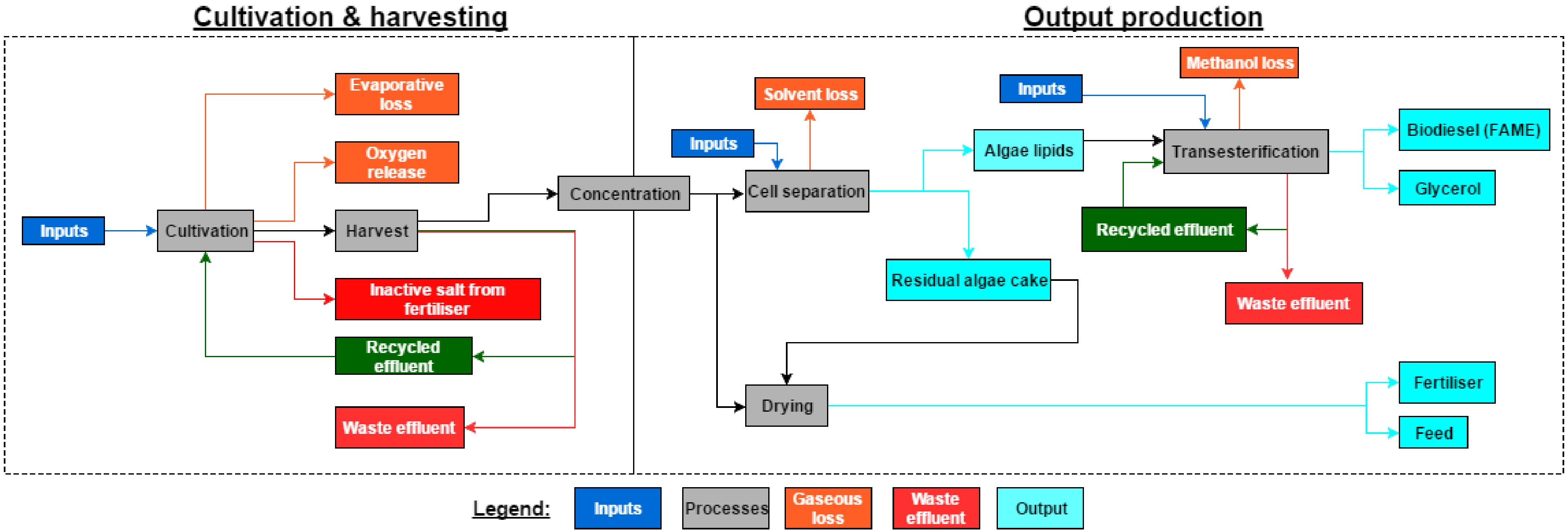


Figure B.2: Spread sheet mass balance framework for cultivation stage.

Calculated cells
Assumptions

Production assumptions cell A36

Inputs		
Algae culture	0.28	t/day
Wastewater	432,331	l/day
Water	432.03	t/day
Carbon	0.0346	t/day
Nitrogen	0.0086	t/day
Phosphorus	0.0017	t/day
CO2	207.29	t/day
Carbon	56.53	t/day
Oxygen	150.75	t/day
Urea	5.890	t/day
Nitrogen	2.710	t/day
Inactive elements	1.463	t/day
DAP	1.420	t/day
Nitrogen	0.256	t/day
Phosphorus	0.653	t/day
Inactive elements	1.060	t/day
Trace elements	8.894	t/day
Total	655.8	t/day
Nitrogen	3.005	t/day
Phosphorus	0.6616	t/day
Carbon	56.72	t/day

Cultivation		
Volume	273,193,840.0	m3
Algae	0.285	t/day
Carbon	0.153	t/day
Nitrogen	0.0311	t/day
Phosphorus	0.00684	t/day
Salt active	0.0937	t/day
Growth medium		
Water	474.8	t/day
Carbon	0.03459	t/day
Nitrogen	0.00865	t/day
Phosphorus	0.00173	t/day
CO2	222.3	t/day
Carbon	60.63	t/day
Oxygen	161.69	t/day
Urea	5.896	t/day
Nitrogen	2.712	t/day
Inactive elements	3.184	t/day
DAP	1.421	t/day
Nitrogen	0.26	t/day
Phosphorus	0.65	t/day
Inactive elements	0.51	t/day
Trace elements	8.89	t/day
Total	713.70	t/day
Nitrogen	3.008	t/day
Phosphorus	0.662	t/day
Carbon	60.82	t/day

Water and CO2 loss		
Water	19.51	t/day
CO2	9.133	t/day
Carbon	2.491	t/day
Oxygen	6.642	t/day
Total	28.64	t/day

Oxygen release		
Oxygen	38.69	t/day

Harvest (wet algae)		
Algae	27.32	t/day
Carbon	14.7	t/day
Nitrogen	2.98	t/day
Phosphorus	0.656	t/day
Salt active	8.99	t/day
Growth medium		
Water	455.3	t/day
Carbon		t/day
Nitrogen		t/day
Phosphorus		t/day
CO2	160.0	t/day
Carbon	43.63	t/day
Oxygen	116.36	t/day
Urea	0.0591	t/day
Nitrogen	0.0272	t/day
Inactive elements	0.0319	t/day
DAP	0.0142	t/day
Nitrogen	0.0026	t/day
Phosphorus	0.0066	t/day
Inactive elements	0.0051	t/day
Total	642.7	t/day
Nitrogen	3.01	t/day
Phosphorus	0.66	t/day
Carbon	58.33	t/day

Spent fertilisers- inactive salt		
Urea (minus N)	3.152	t/day
DAP (minus N,P)	0.506	t/day
Total	3.658	t/day

Recycled effluent		
Wastewater		
Water	42.80	t/day
Carbon		t/day
Nitrogen		t/day
Phosphorus		t/day
CO2	15.04	t/day
Carbon	4.102	t/day
Oxygen	10.938	t/day
Urea	0.006	t/day
Nitrogen	0.00256	t/day
Inactive elements	0.00300	t/day
DAP	0.00134	t/day
Nitrogen	0.00024	t/day
Phosphorus	0.00062	t/day
Inactive elements	0.00048	t/day
Total	57.85	t/day
Nitrogen	0.00280	t/day
Phosphorus	0.000616	t/day
Carbon	4.10	t/day

Concentration		
Water	27.32	t/day
Algae	27.32	t/day
Proteins	1.91	t/day
Lipids	10.93	t/day
Carbohydrates	13.66	t/day
Nucleic acid	0.82	t/day
CO2	9.599	t/day
Carbon	2.618	t/day
Oxygen	6.981	t/day
Urea	0.00355	t/day
Nitrogen	0.001632	t/day
Inactive elements	0.00192	t/day
DAP	0.000855	t/day
Nitrogen	0.000154	t/day
Phosphorus	0.000393	t/day
Inactive elements	0.000308	t/day
Total	64.24	t/day
Nitrogen	2.980	t/day
Phosphorus	0.6561	t/day
Carbon	17.32	t/day

Waste effluent		
Wastewater		
Water	385.2	t/day
Carbon		t/day
Nitrogen		t/day
Phosphorus		t/day
CO2	135.4	t/day
Carbon	36.91	t/day
Oxygen	98.44	t/day
Urea	0.050	t/day
Nitrogen	0.0230	t/day
Inactive elements	0.0270	t/day
DAP	0.0121	t/day
Nitrogen	0.002170	t/day
Phosphorus	0.00554	t/day
Inactive elements	0.00434	t/day
Total	520.6	t/day
Nitrogen	0.02518	t/day
Phosphorus	0.00554	t/day
Carbon	36.91	t/day

Figure B.3: Spread sheet mass balance framework for cell-separation and drying stages.

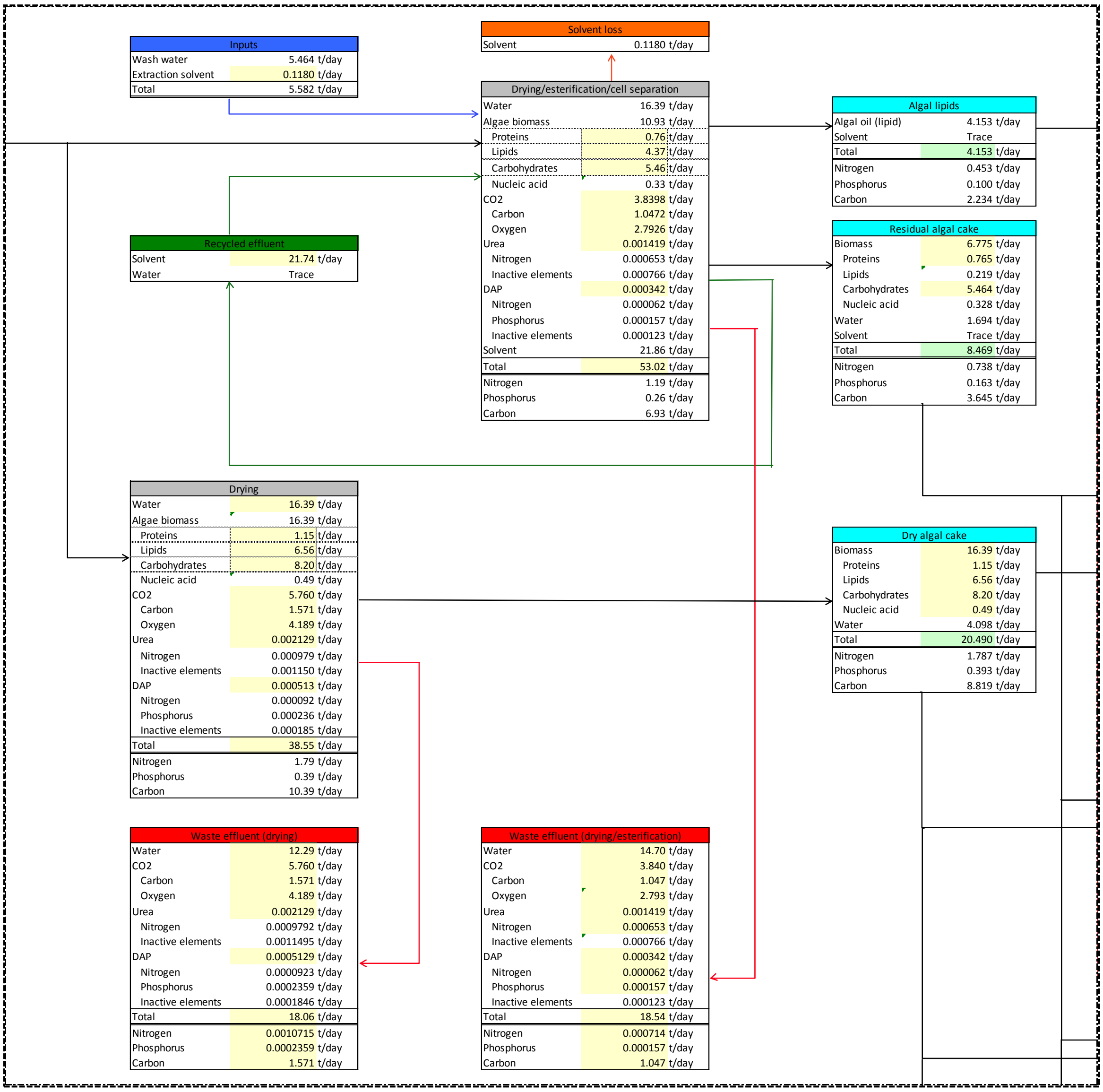


Figure B.4: Spread sheet mass balance framework for output production stage.

Inputs		
Methanol	0.488	t/day
KOH (50%)	0.125	t/day
Water	0.229	t/day
Phosphoric acid (60%)	0.052	t/day
Total	0.89	t/day

Transesterification		
Algal oil	4.153	t/day
Methanol in	0.947	t/day
KOH neat	0.062	t/day
Phosphoric acid neat	0.031	t/day
Water	0.312	t/day
Total	5.50	t/day

Methanol loss		
Methanol	0.0191	t/day

Transesterification outputs		
Biodiesel (FAME)	4.13	t/day
Glycerol	0.45	t/day
Total	4.58	t/day

Recycled effluent		
Methanol out	0.459	t/day

Waste effluent			
Biodiesel unrecovered	0.000139	t/day	
Water	0.329	t/day	
Soaps	0.045	t/day	
Glycerol	0.005	t/day	
Potassium Phosphate (salt)	0.068	t/day	assume tri-potassium phosphate
Total	0.447	t/day	

Agricultural fertiliser		
Fertiliser	11.58	t/day
Proteins	0.96	t/day
Lipids	3.39	t/day
Carbohydrates	6.83	t/day
Nucleic Acid	0.41	t/day
Water	1.29	t/day
Total	12.87	t/day
Nitrogen	1.26	t/day
Phosphorus	0.278	t/day
Carbon	6.23	t/day

	Nutrient %
Proteins	8%
Lipids	29%
Carbohydrates	59%
N	11%
P	2%

Drying for aquaculture feed		
Water	1.61	t/day

Feed		
Feed	11.58	t/day
Proteins	0.96	t/day
Lipids	3.39	t/day
Carbohydrates	6.83	t/day
Nucleic acid	0.41	t/day
Water	1.58	t/day
Total	13.16	t/day
Nitrogen	1.263	t/day
Phosphorus	0.278	t/day
Carbon	6.232	t/day

	Nutrient %
Protein	8%
Lipids	29%
Carbohydrates	59%
N	11%
P	2%

Drying for aquaculture feed		
Water	1.32	t/day

Appendix C

The summary statistics for the TEA profit function simulations of 5000 runs, including those with a negative NPV, is given in Table C.1 below. The negative NPV scenarios were dropped in the final analysis to exclude unlikely production scenarios.

Table C.1: Summary of all simulation data (n=5000).

Parameters	Mean	SD	Min	Max
Output parameters				
Price of biodiesel (US$/l)	1.63	0.26	1.18	2.08
Quantity of biodiesel (l)	3,005,253.81	1,456,031.80	520,816.24	7,240,428.81
Price of fertiliser (US$/kg)	16.54	4.33	9.00	24.00
Quantity of fertiliser (kg)	6,834,660.78	4,319,617.11	101,748.35	22,206,165.31
Price of feed (US$/kg)	10.27	4.46	2.51	18.00
Quantity of feed (kg)	6,784,689.53	4,315,142.34	120,092.32	22,032,199.33
Input parameters				
Energy parameters				
Electricity price (US$/kW)	0.41	0.06	.30	0.52
Quantity of electricity (kW)	1,608,657.77	663,151.85	460,126.86	2,758,683.89
Natural gas price (US$/GJ)	7.50	1.71	4.54	10.46
Quantity of gas (GJ)	65,618.27	27,914.87	16,264.76	133,854.28
Fertilisers parameters				
Urea price (US$/t)	493.75	214.23	121.67	870.32
Quantity of urea (t)	3,503.24	1,444.17	1,002.04	6,007.70
DAP price (US$/t)	817.24	337.43	227.41	1,409.49
Quantity of DAP (t)	844.33	348.07	241.50	1,447.94
Other input parameters				
Water price (US$/t)	3.99	1.24	1.86	6.14
Quantity of water (t)	4,034.11	2,546.61	406.01	12,821.77
Methanol price (US$/t)	457.25	150.92	200.30	719.99
Quantity of methanol (t)	308.83	149.63	53.52	744.04
Maintenance parameters				
Maintenance cost factor	1.00	0.12	0.80	1.20
Maintenance costs (US$)	39,094,598.39	10,971,155.97	14,682,625.71	72,056,835.66

Appendix D

This section presents the share equations for diesel, fertiliser output, energy, and fertiliser inputs. The coefficients of these equations are restricted accordingly and hence, are represented by the corresponding coefficients in the main profit function.

Table D.1: Estimated from biodiesel share function.

Variable	Coeff.		S.E.
Intercept	0.0320	***	0.0003
Biodiesel price	0.0238	***	0.0010
Fertiliser(out) price	-0.0366	***	0.0017
Energy price	0.0018	***	0.0005
Fertiliser(in) price	-0.0009		0.0006
Maintenance price	0.0160	***	0.0017
Growth rate	0.0033	***	0.0006
Adj. R^2	0.320		

‘***’ Significant at 1%, ‘**’ Significant at 5%, ‘*’ Significant at 10%

Table D.2: Estimates from fertiliser(out) share function.

Variable	Coeff.		S.E.
Intercept	0.7704	***	0.0039
Biodiesel price	-0.0366	***	0.0017
Fertiliser(out) price	0.2658	***	0.0248
Energy price	0.0069	***	0.0013
Fertiliser(in) price	0.0227	***	0.0032
Maintenance price	0.0858	***	0.0251
Growth rate	-0.0041	***	0.0011
Adj. R^2	0.315		

‘***’ Significant at 1%, ‘**’ Significant at 5%, ‘*’ Significant at 10%

Table D.3: Estimates from energy share function.

Variable	Coeff.		S.E.
Intercept	-0.0078	***	0.0002
Biodiesel price	0.0018	***	0.0005
Fertiliser(out) price	0.0069	***	0.0013
Energy price	-0.0020	***	0.0004
Fertiliser(in) price	0.0004		0.0005
Maintenance price	-0.0077	***	0.0013
Growth rate	-0.0012	**	0.0005
Adj. R^2	0.307		

'***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%

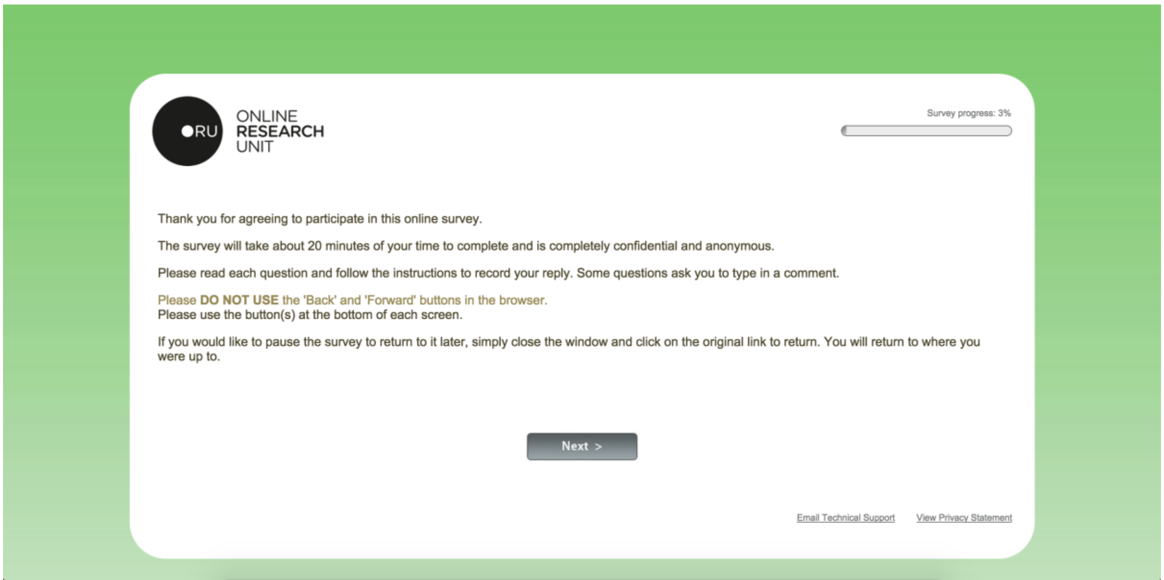
Table D.4: Estimates from fertiliser(in) share function.

Variable	Coeff.		S.E.
Intercept	-0.0164	***	0.0005
Biodiesel price	-0.0009		0.0006
Fertiliser(out) price	0.0227	***	0.0032
Energy price	0.0004		0.0005
Fertiliser(in) price	-0.0117	***	0.0013
Maintenance price	-0.0104	***	0.0032
Growth rate	-0.0041	***	0.0011
Adj. R^2	0.471		

'***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%

Appendix E

This section presents the screenshots of a test link for the online DCE survey that was hosted by Online Research Unit (ORU). The first part is the participant information sheet that all prospective respondents were asked to read prior to proceeding. Participants were also able to download a version of this sheet to keep. Then, a version of the survey is presented. All multiple options and sub-questions are shown accordingly. The choice experiment section presents one of the four blocks of the post-pilot experiment design. Ethical clearance for this survey was approved by Queensland University of Technology's University Human Ethics Research Committee (approval number: 1500000634).


ONLINE RESEARCH UNIT

Survey progress: 3%

Thank you for agreeing to participate in this online survey.

The survey will take about 20 minutes of your time to complete and is completely confidential and anonymous.

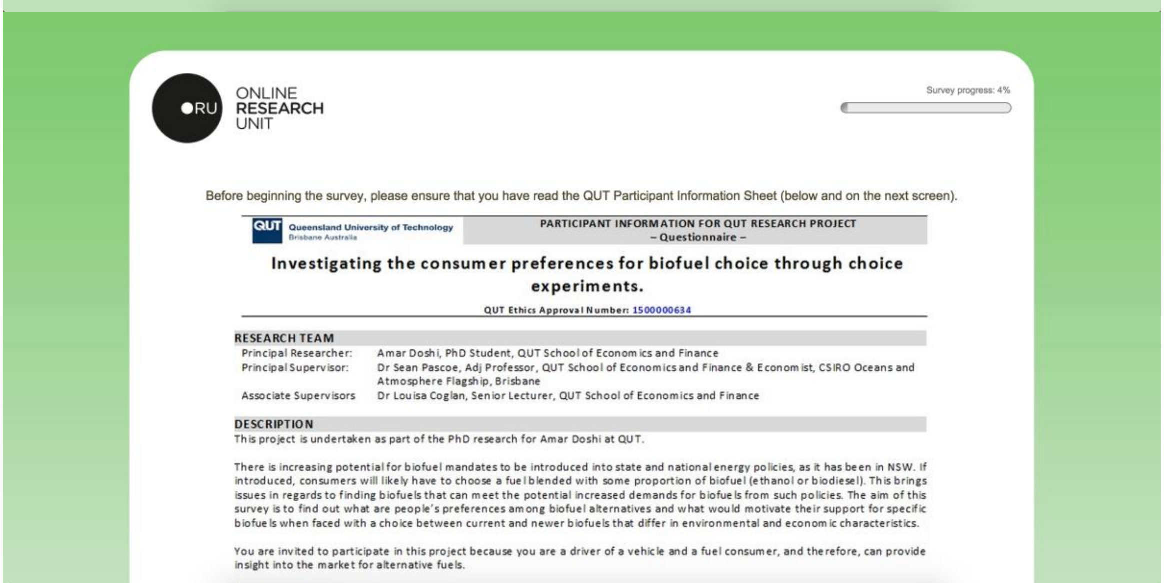
Please read each question and follow the instructions to record your reply. Some questions ask you to type in a comment.

Please **DO NOT USE** the 'Back' and 'Forward' buttons in the browser.
Please use the button(s) at the bottom of each screen.

If you would like to pause the survey to return to it later, simply close the window and click on the original link to return. You will return to where you were up to.

Next >

Email Technical Support | View Privacy Statement


ONLINE RESEARCH UNIT

Survey progress: 4%

Before beginning the survey, please ensure that you have read the QUT Participant Information Sheet (below and on the next screen).

Queensland University of Technology
Brisbane Australia

PARTICIPANT INFORMATION FOR QUT RESEARCH PROJECT
– Questionnaire –

Investigating the consumer preferences for biofuel choice through choice experiments.

QUT Ethics Approval Number: 1500000634

RESEARCH TEAM

Principal Researcher:	Amar Doshi, PhD Student, QUT School of Economics and Finance
Principal Supervisor:	Dr Sean Pascoe, Adj Professor, QUT School of Economics and Finance & Economist, CSIRO Oceans and Atmosphere Flagship, Brisbane
Associate Supervisors	Dr Louisa Coglan, Senior Lecturer, QUT School of Economics and Finance

DESCRIPTION

This project is undertaken as part of the PhD research for Amar Doshi at QUT.

There is increasing potential for biofuel mandates to be introduced into state and national energy policies, as it has been in NSW. If introduced, consumers will likely have to choose a fuel blended with some proportion of biofuel (ethanol or biodiesel). This brings issues in regards to finding biofuels that can meet the potential increased demands for biofuels from such policies. The aim of this survey is to find out what are people's preferences among biofuel alternatives and what would motivate their support for specific biofuels when faced with a choice between current and newer biofuels that differ in environmental and economic characteristics.

You are invited to participate in this project because you are a driver of a vehicle and a fuel consumer, and therefore, can provide insight into the market for alternative fuels.

PARTICIPATION

Your participation in this study will involve completing a survey questionnaire anonymously, which consists of 26 questions will take about 20-30 minutes. The questions will detail your current transport and fuel usage, your perceptions on fuel availability in Australia, your socio-economic background, and your choices when comparing a range of biofuel alternatives. This survey will only provide non-identifiable information. Some sample questions are given below.

Example 1: How many motor vehicles do you own i.e. bought under your name (including motorcycles/mopeds/scooters)?

Example 2: Please consider each option below and choose your most preferred option.

Attribute		Biofuel A	Biofuel B	Biofuel C
Emissions		25% Reduction	25% More	No change
Source		Imported	Local	Imported
Food price		10% Cheaper	10% More expensive	No change
Biodiversity		25% Loss	25% Gain	No change
Fuel price		10% More expensive	10% Cheaper	No change

Example 3: Are you a member of an international or local environmental group?

If you happen to feel tired while completing the survey, you are able to stop and save your answers at any point and return to the same point when you are able to continue within the same day. If you do not complete the survey in the same day, the data you have submitted at the point you stopped will not be used for the study.

Your participation is completely voluntary. You are not required to complete questions that you are uncomfortable with, even after agreeing to participate, although your complete responses will be beneficial to the study. Your decision to participate will not affect any current or future relationship you may have with any of the participating institutions i.e. QUT, CSIRO. If you do not wish to participate, you can withdraw without comment or penalty. However, as this survey is anonymous, it will not be possible to withdraw once it has been submitted.

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ONLINE RESEARCH UNIT

Survey progress: 5%

EXPECTED BENEFITS

It is expected that this project will not directly benefit you. However, it may result in several benefits as below

- It will fill gaps in knowledge regarding consumer preferences in regards to biofuels. The findings will provide useful information to biofuel developers, investors, and policymakers on the potential for current and future biofuel alternatives.
- A monetary value for various environmental and economic benefits will be estimated through analysis from the survey. This will provide an indication to policymakers to the societal value of these benefits and suggest the magnitude of policy intervention to ensure more efficient pricing.
- With the growth of a microalgae biofuels, the findings from this study will help to estimate the associated benefits of microalgae biofuels against more conventional biofuels and suggest its potential in biofuel-related policies.

A report detailing the questionnaire's results can be emailed to you upon request upon completion of the analysis in mid-2016. You can request for a copy of these results by contacting one of the researchers listed below.

RISKS

There are no risks beyond normal day-to-day living associated with your participation in this project.

PRIVACY AND CONFIDENTIALITY

All comments and responses are anonymous and will be treated confidentially unless required by law. The names of individual persons are not required in any of the responses.

Any data collected as part of this project will be stored securely as per QUT's Management of research data policy. Please note that non-identifiable data collected in this project will be shared with CSIRO for the purposes of receiving advice for analysis. The data may also be used as comparative data in future projects in an unidentifiable form including future collaborative research with other organisations.

CONSENT TO PARTICIPATE

Submitting the completed online questionnaire is accepted as an indication of your consent to participate in this project.

QUESTIONS / FURTHER INFORMATION ABOUT THE PROJECT

If have any questions or require further information please contact one of the research team members below.

Amar Doshi – PhD Student   Dr Sean Pascoe – Adj Professor (QUT), Economist (CSIRO)

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Amar Doshi – PhD Student	Dr Sean Pascoe – Adj Professor (QUT), Economist (CSIRO)
School of Economics and Finance	School of Economics and Finance, QUT Business School
QUT Business School	Oceans and Atmosphere Flagship, CSIRO
07 3138 4711	07 3833 5966
amar.doshi@hdr.qut.edu.au	sean.pascoe@qut.edu.au/sean.pascoe@csiro.au

CONCERNS / COMPLAINTS REGARDING THE CONDUCT OF THE PROJECT

QUT is committed to research integrity and the ethical conduct of research projects. However, if you do have any concerns or complaints about the ethical conduct of the project you may contact the QUT Research Ethics Unit on [+61 7] 3138 5123 or email ethicscontact@qut.edu.au. The QUT Research Ethics Unit is not connected with the research project and can facilitate a resolution to your concern in an impartial manner.

Thank you for helping with this research project. Please keep this sheet for your information.

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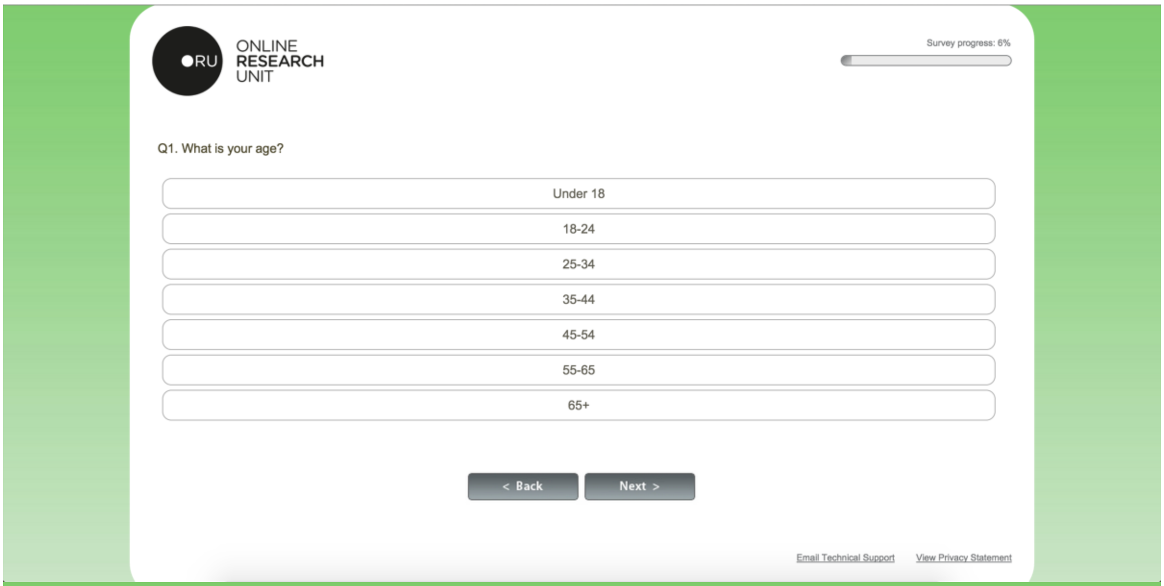

ORU ONLINE RESEARCH UNIT

Survey progress: 6%

Q1. What is your age?

- Under 18
- 18-24
- 25-34
- 35-44
- 45-54
- 55-65
- 65+

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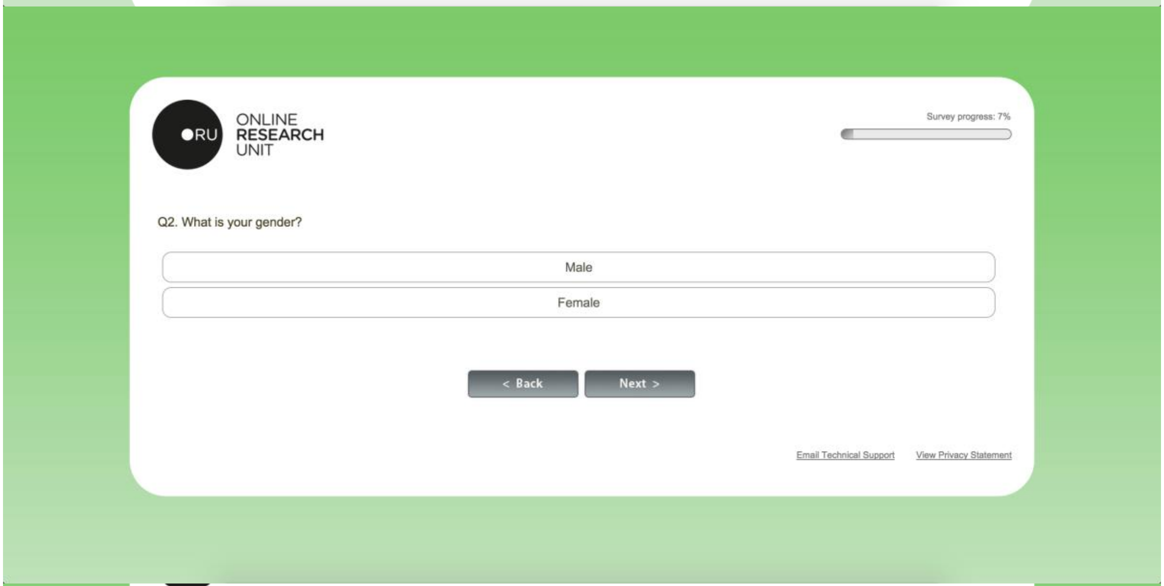

ORU ONLINE RESEARCH UNIT

Survey progress: 7%

Q2. What is your gender?

- Male
- Female

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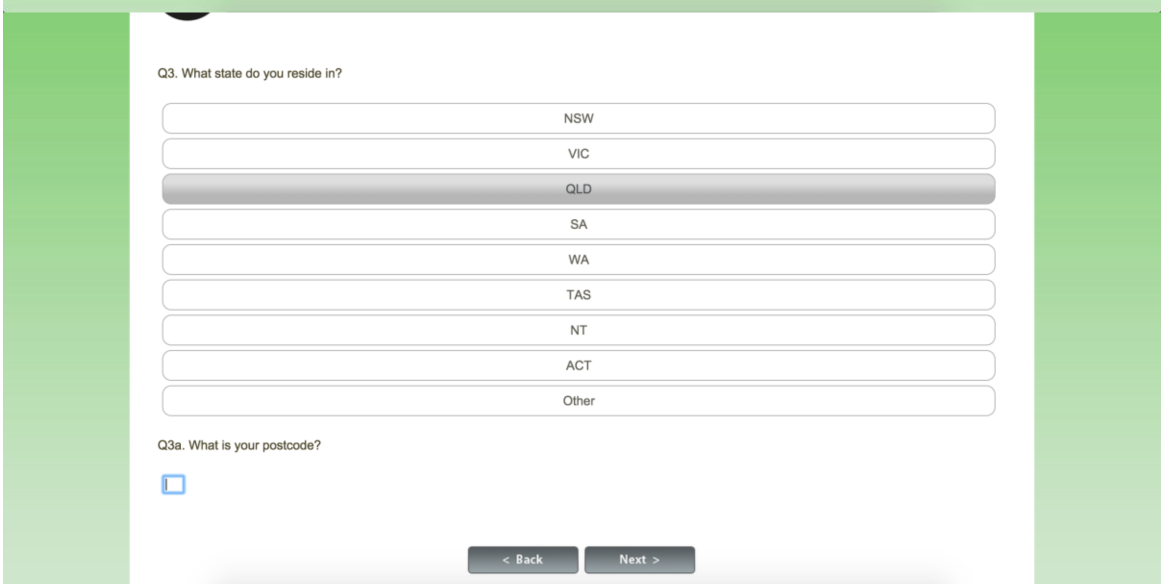

Q3. What state do you reside in?

- NSW
- VIC
- QLD
- SA
- WA
- TAS
- NT
- ACT
- Other

Q3a. What is your postcode?

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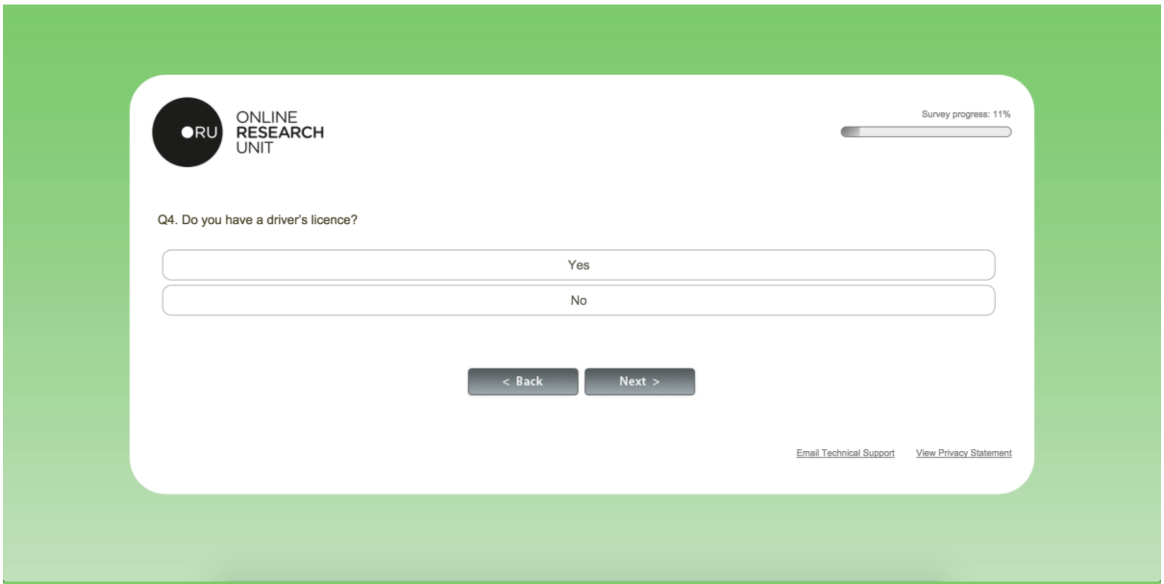
ONLINE RESEARCH UNIT
Survey progress: 11%
Q4. Do you have a driver's licence?
Yes
No
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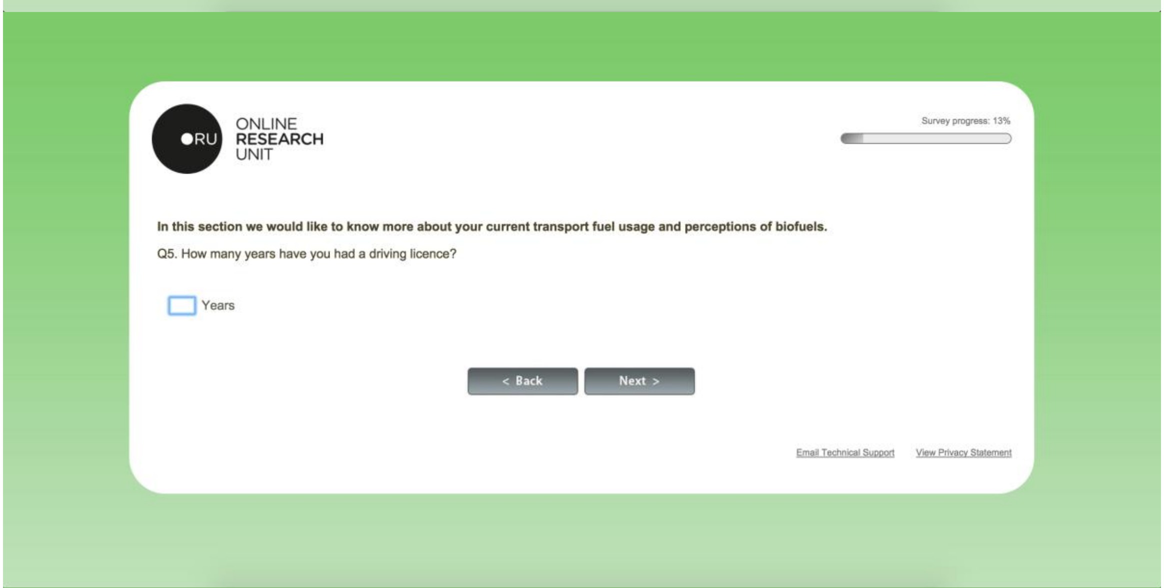
ONLINE RESEARCH UNIT
Survey progress: 13%
In this section we would like to know more about your current transport fuel usage and perceptions of biofuels.
Q5. How many years have you had a driving licence?
Years
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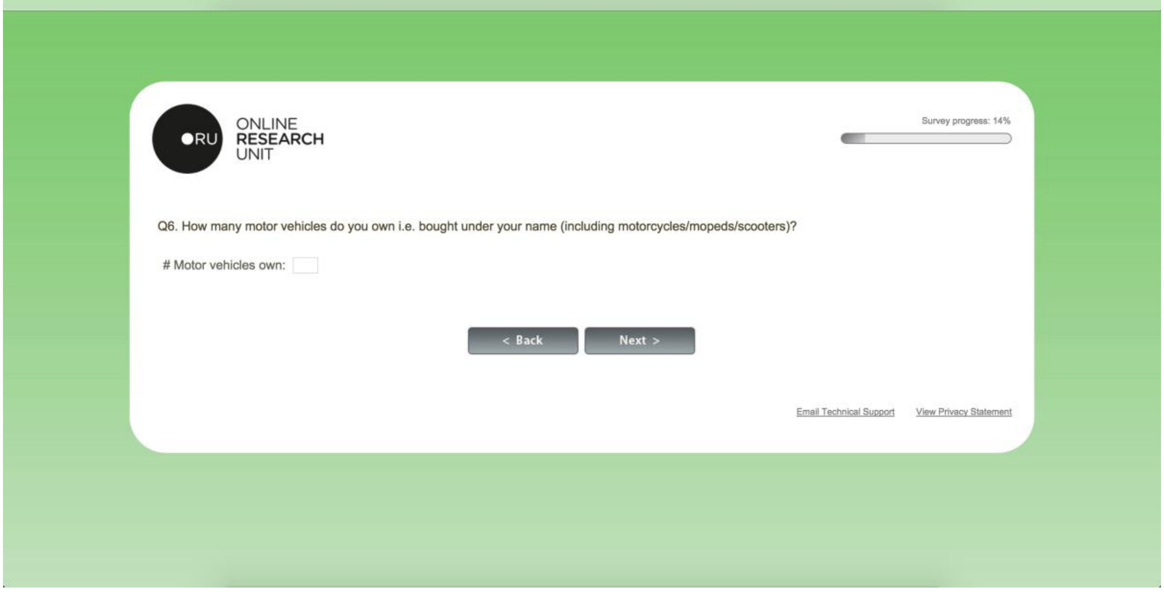
ONLINE RESEARCH UNIT
Survey progress: 14%
Q6. How many motor vehicles do you own i.e. bought under your name (including motorcycles/mopeds/scooters)?
Motor vehicles own:
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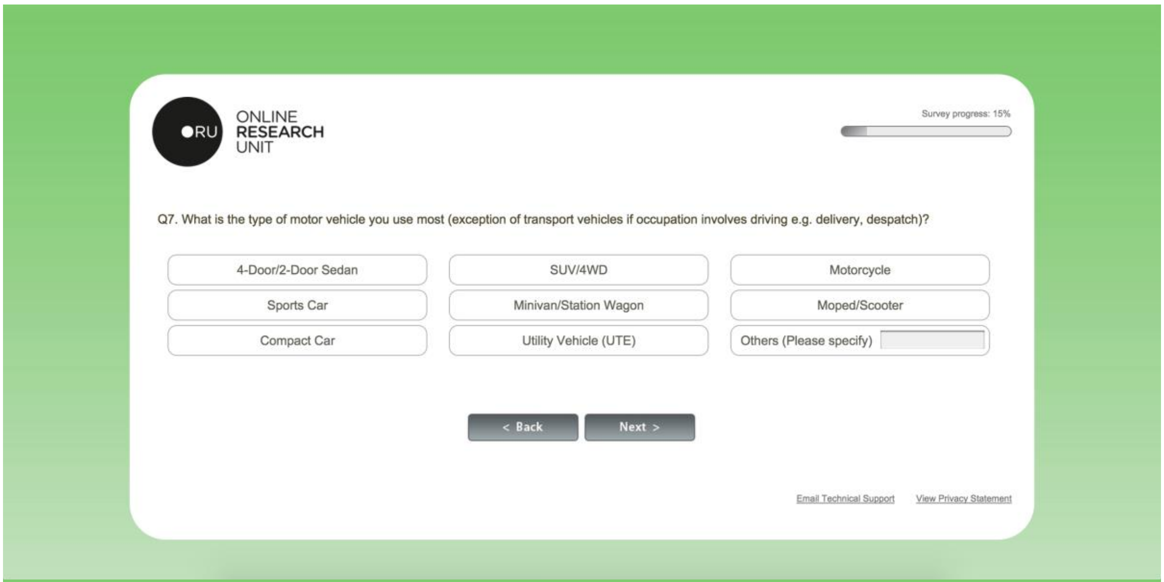

ONLINE RESEARCH UNIT

Survey progress: 15%

Q7. What is the type of motor vehicle you use most (exception of transport vehicles if occupation involves driving e.g. delivery, despatch)?

4-Door/2-Door Sedan	SUV/4WD	Motorcycle
Sports Car	Minivan/Station Wagon	Moped/Scooter
Compact Car	Utility Vehicle (UTE)	Others (Please specify)

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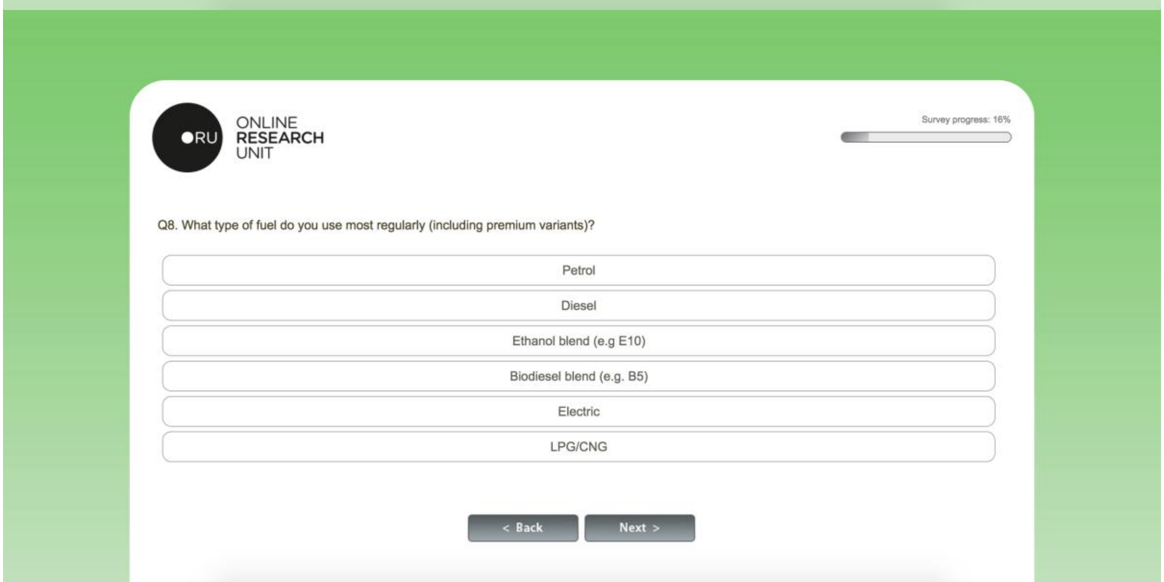

ONLINE RESEARCH UNIT

Survey progress: 16%

Q8. What type of fuel do you use most regularly (including premium variants)?

- Petrol
- Diesel
- Ethanol blend (e.g E10)
- Biodiesel blend (e.g. B5)
- Electric
- LPG/CNG

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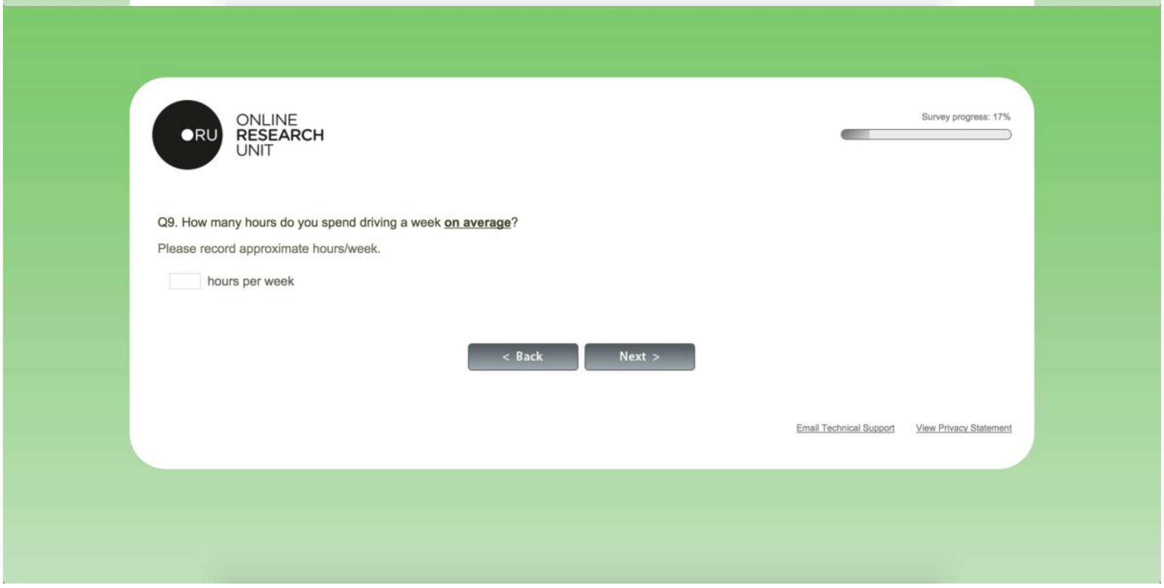

ONLINE RESEARCH UNIT

Survey progress: 17%

Q9. How many hours do you spend driving a week **on average**?

Please record approximate hours/week.

hours per week

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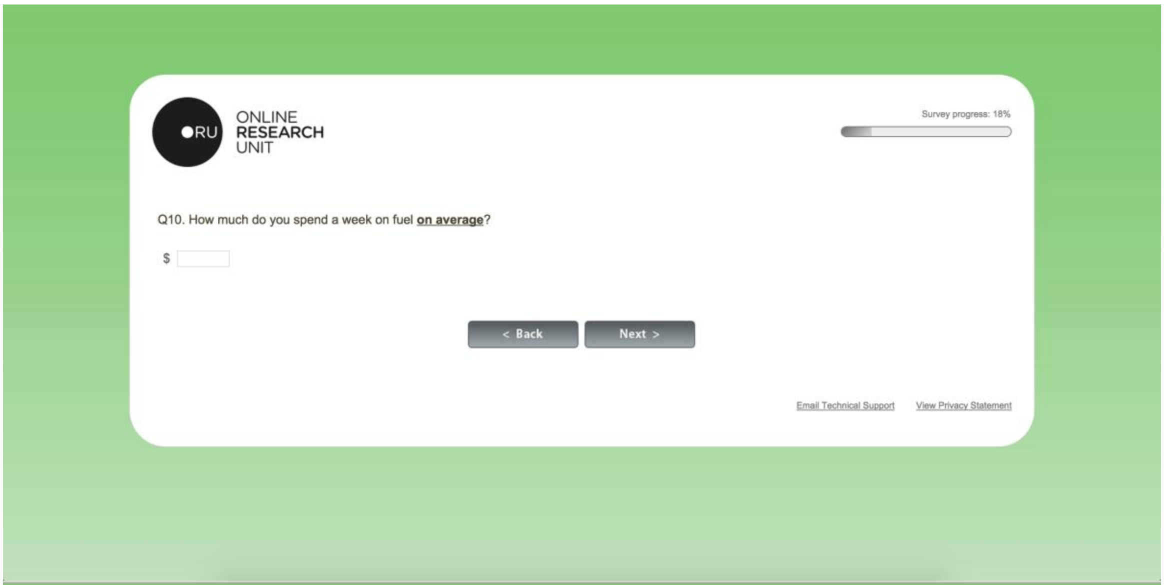
ONLINE RESEARCH UNIT

Survey progress: 18%

Q10. How much do you spend a week on fuel **on average**?

$

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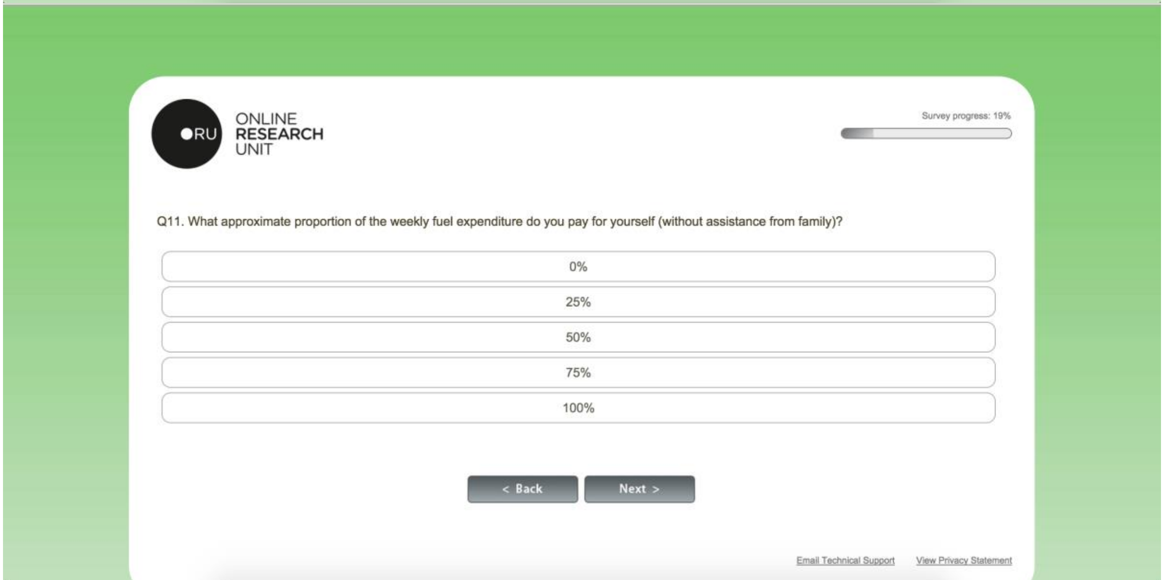
ONLINE RESEARCH UNIT

Survey progress: 19%

Q11. What approximate proportion of the weekly fuel expenditure do you pay for yourself (without assistance from family)?

0%

25%

50%

75%

100%

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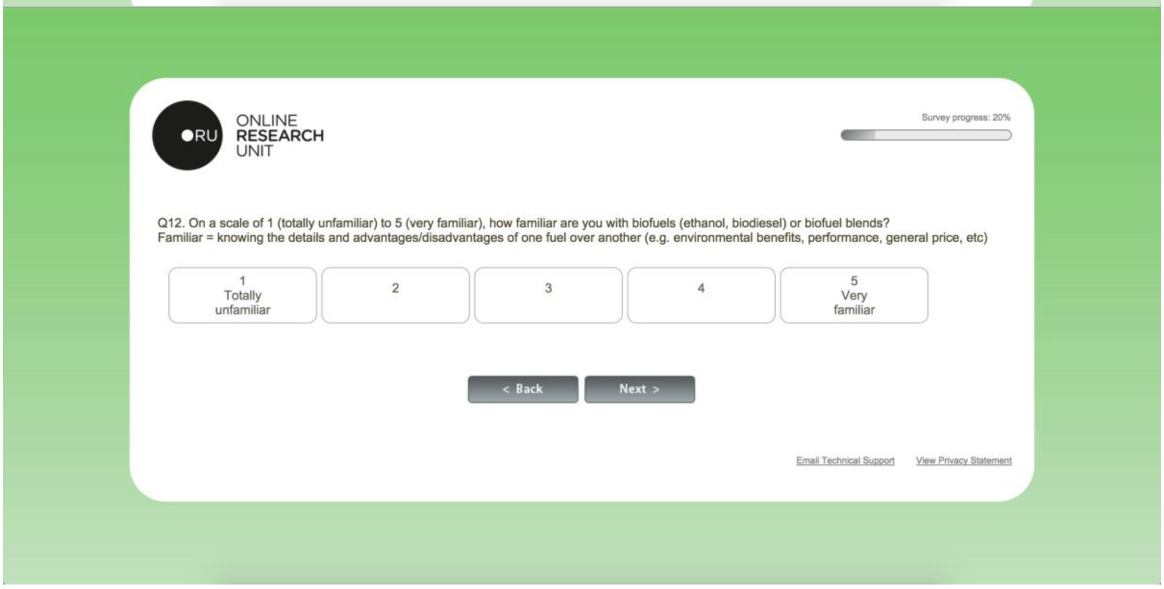
ONLINE RESEARCH UNIT

Survey progress: 20%

Q12. On a scale of 1 (totally unfamiliar) to 5 (very familiar), how familiar are you with biofuels (ethanol, biodiesel) or biofuel blends?
Familiar = knowing the details and advantages/disadvantages of one fuel over another (e.g. environmental benefits, performance, general price, etc)

1 Totally unfamiliar	2	3	4	5 Very familiar

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Q13. Do you use biofuels regularly?

Yes

No

Q13a. which kind?

Ethanol (blend)

Biodiesel (blend)

Other (Please specify)

Q13b. Why?

Please select all that apply.

Good for environment

Bought a vehicle that runs specifically on biofuel

Cheaper

Other (Please specify)

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Q13. Do you use biofuels regularly?

Yes

No

Q13c. Why not?

Please select all that apply.

Too expensive

Does not give the same performance/not reliable

I know/think my vehicle is not suited/recommended for biofuels

Not available in my area/local stations

Never considered using biofuels

No benefit over regular petrol/diesel

Other (Please specify)

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ORU ONLINE RESEARCH UNIT

Survey progress: 24%

Q13d. How interested are you in using biofuels?

1 Not at all interested	2	3	4	5 Extremely interested

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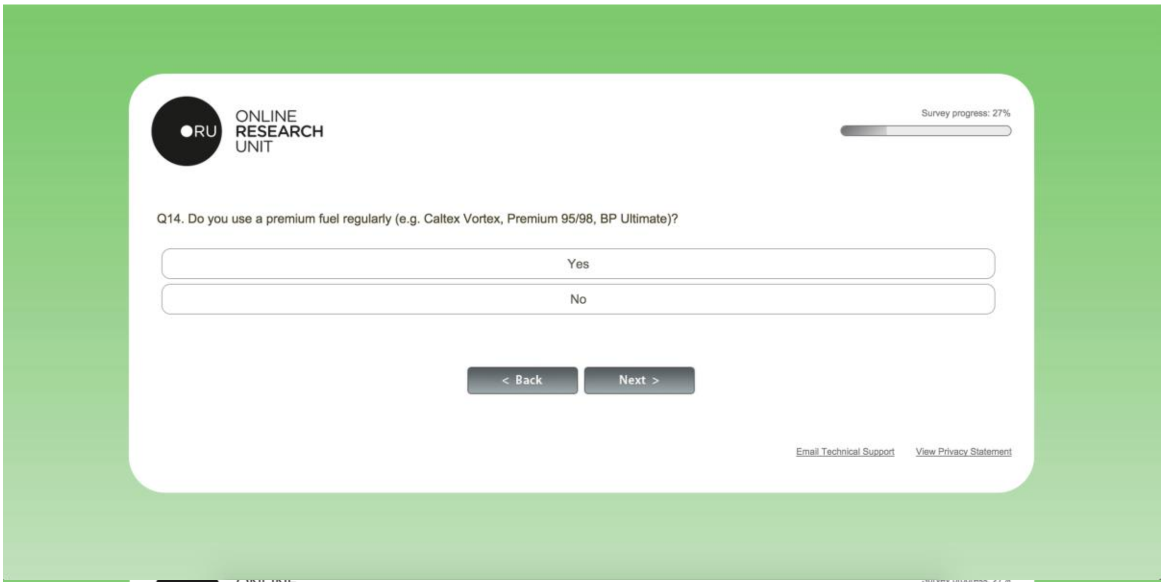
ONLINE RESEARCH UNIT
Survey progress: 27%
Q14. Do you use a premium fuel regularly (e.g. Caltex Vortex, Premium 95/98, BP Ultimate)?
Yes
No
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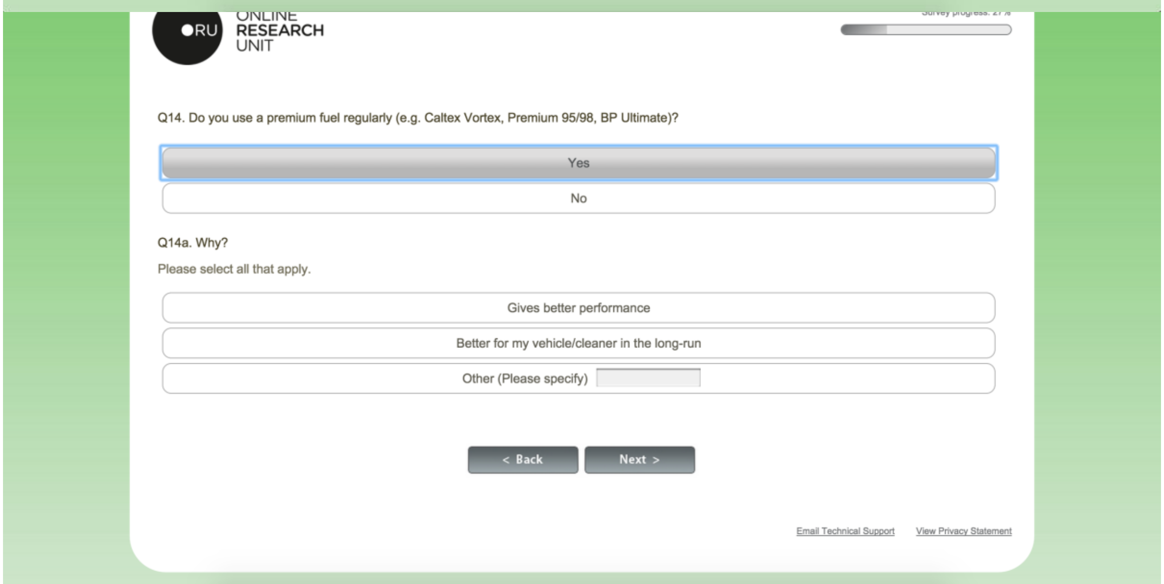
ONLINE RESEARCH UNIT
Q14. Do you use a premium fuel regularly (e.g. Caltex Vortex, Premium 95/98, BP Ultimate)?
Yes
No
Q14a. Why?
Please select all that apply.
Gives better performance
Better for my vehicle/cleaner in the long-run
Other (Please specify)
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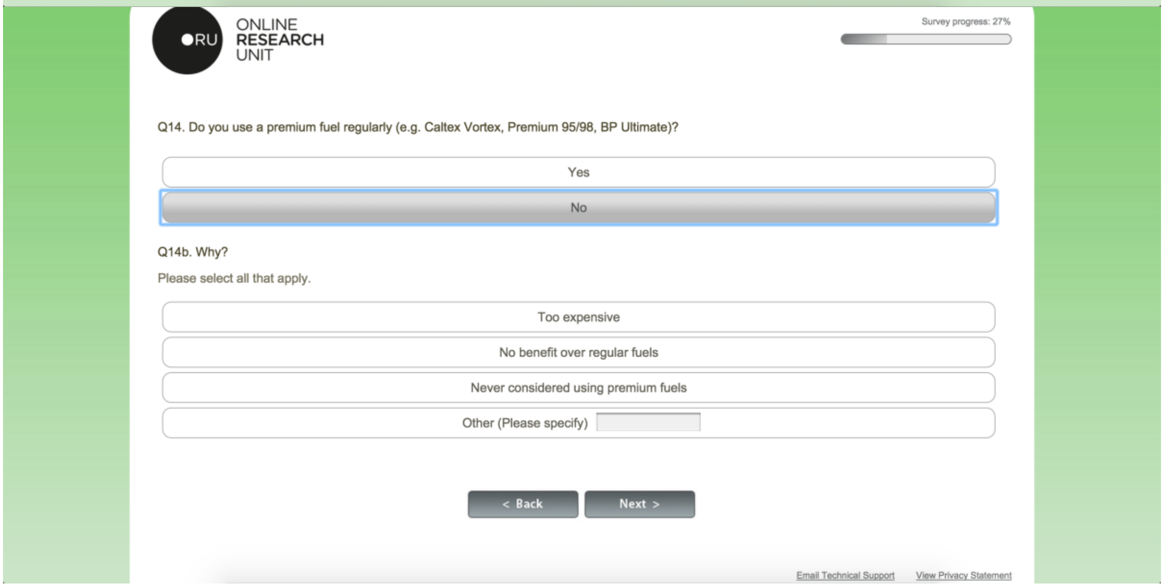
ONLINE RESEARCH UNIT
Survey progress: 27%
Q14. Do you use a premium fuel regularly (e.g. Caltex Vortex, Premium 95/98, BP Ultimate)?
Yes
No
Q14b. Why?
Please select all that apply.
Too expensive
No benefit over regular fuels
Never considered using premium fuels
Other (Please specify)
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ONLINE RESEARCH UNIT

Survey progress: 28%

Biofuel mandates have been an increasingly common point of discussion among policymakers. These mandates require a minimum amount of fuel sold to include biofuels. Currently, NSW is the only state with an existing biofuel mandate, but state and national biofuels policies have remained a topic of interest in Australia. At some point in the future, only fuels containing some amount of biofuel (ethanol or biodiesel) may be available with no option of 100% regular petrol or diesel.

Biofuels can be produced from a number of plant-sources but this has raised issues (which are not limited to) as described below.

Emissions
While biofuels can have lower carbon dioxide emissions than petrol/diesel, the cultivation of the crop/plant biomass has also been found to absorb carbon dioxide from the atmosphere. The amount of carbon dioxide absorbed during cultivation varies according to the type of crop/plants but can also be cancelled out during the processing into biofuels.

Source
Studies have suggested that it may not be economical to produce certain biofuels in Australia and as such, part of the biofuel supply will depend on foreign imports (20-50%). This is dependent on the crop/plant type, production technologies, and the availability of sufficient resources to produce them.

Food price
Increasing production of certain crop/plant-based biofuels can result in competition for crops and other resources (e.g. water, land), resulting in higher food prices. Others can potentially reduce food prices by reducing such competition.

Biodiversity
Increasing production of some biofuels can result in clearing of forests and/or expansion of agricultural land, which has been found to affect the richness in diversity of bird, animal, and plant species native to specific farmland and forests. These impacts on biodiversity are dependent on the type of crop/plants, with some potentially increasing biodiversity by reducing need for such land clearing.

Price
Biofuels are generally more expensive than petrol/diesel but some biofuels are cheaper than others based on cultivation and processing technologies.

In this section we would like you to consider scenarios where the state you live in has introduced a new biofuel mandate and you have been asked to choose the type of biofuel you most prefer to purchase. These biofuels differ in terms of the type of plant used to produce the fuel and as such, have different characteristics. Please assume that you would not be able to purchase unblended fuels.

Price
Biofuels are generally more expensive than petrol/diesel but some biofuels are cheaper than others based on cultivation and processing technologies.

In this section we would like you to consider scenarios where the state you live in has introduced a new biofuel mandate and you have been asked to choose the type of biofuel you most prefer to purchase. These biofuels differ in terms of the type of plant used to produce the fuel and as such, have different characteristics. Please assume that you would not be able to purchase unblended fuels.

Each fuel is assumed to have the same effects on performance and mileage of your vehicle, and your vehicle can run on any of the fuels without having to modify your vehicle in any way. The only differences between the fuels are represented by the attributes given in each scenario as described below. Please make your decisions independently of each other.

Your state is currently choosing to supply Biofuel C. Please choose the biofuel that you would support as the option for your state (Biofuel A, B, or C), assuming you will have to purchase a biofuel-blend containing one of these options. The biofuels differ in the following attributes.

Attributes	Description
Emissions	Change in net emissions taking into account cultivation and processing relative to Biofuel C.
Source	Indicator of the source of the fuel, either being completely produced in Australia or partially imported.
Food price	Estimated impact on food prices from the increased production of the fuel and competition for agricultural resources relative to Biofuel C.
Biodiversity	Impact on species richness as a result of production of the fuel relative to Biofuel C.
Price	Price of fuel sold relative to Biofuel C.

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Scenario 1:

Consider the following three biofuel options. Assuming these are the only options available to you, which one would you choose?

Attribute	Biofuel A	Biofuel B	Biofuel C
Emissions	25% Reduction	25% More	No change
Source	Imported	Local	Imported
Food price	10% Cheaper	No change	No change
Biodiversity	25% Loss	25% Gain	No change
Fuel price	10% More expensive	10% Cheaper	No change

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Scenario 2:

Consider the following three biofuel options. Assuming these are the only options available to you, which one would you choose?

Attribute	Biofuel A	Biofuel B	Biofuel C
Emissions	50% Reduction	50% More	No change
Source	Local	Imported	Imported
Food price	10% Cheaper	10% More expensive	No change
Biodiversity	50% Gain	50% Loss	No change
Fuel price	10% More expensive	10% Cheaper	No change

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Scenario 3:

Consider the following three biofuel options. Assuming these are the only options available to you, which one would you choose?

Attribute	Biofuel A	Biofuel B	Biofuel C
Emissions	50% Reduction	50% More	No change
Source	Imported	Local	Imported
Food price	20% More expensive	20% Cheaper	No change
Biodiversity	50% Loss	50% Gain	No change
Fuel price	10% Cheaper	10% More expensive	No change

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Scenario 6:

Consider the following three biofuel options. Assuming these are the only options available to you, which one would you choose?

Attribute	Biofuel A	Biofuel B	Biofuel C
Emissions	50% More	50% Reduction	No change
Source	Local	Imported	Imported
Food price	10% More expensive	20% Cheaper	No change
Biodiversity	25% Loss	25% Gain	No change
Fuel price	20% More expensive	20% Cheaper	No change

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Scenario 7:

Consider the following three biofuel options. Assuming these are the only options available to you, which one would you choose?

Attribute		Biofuel A	Biofuel B	Biofuel C
Emissions		50% More	50% Reduction	No change
Source		Local	Imported	Imported
Food price		20% Cheaper	20% More expensive	No change
Biodiversity		50% Gain	50% Loss	No change
Fuel price		20% More expensive	20% Cheaper	No change

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Scenario 8:

Consider the following three biofuel options. Assuming these are the only options available to you, which one would you choose?

Attribute		Biofuel A	Biofuel B	Biofuel C
Emissions		50% More	50% Reduction	No change
Source		Local	Imported	Imported
Food price		20% More expensive	20% Cheaper	No change
Biodiversity		50% Loss	25% Gain	No change
Fuel price		20% More expensive	20% Cheaper	No change

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ORU ONLINE RESEARCH UNIT

Survey progress: 88%

We would like to know how you made your choices.

Q16a. How important were each of the attributes when you were making your choices?

Price

Not important | Slightly important | Important | Very important

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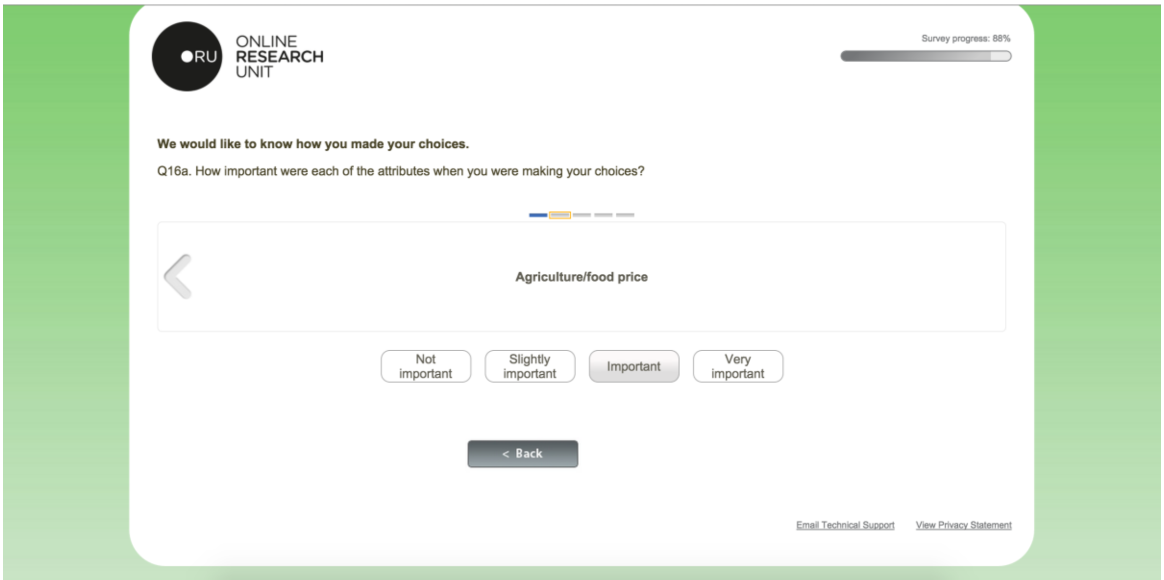
ONLINE RESEARCH UNIT
Survey progress: 88%
We would like to know how you made your choices.
Q16a. How important were each of the attributes when you were making your choices?
Agriculture/food price
Not important
Slightly important
Important
Very important
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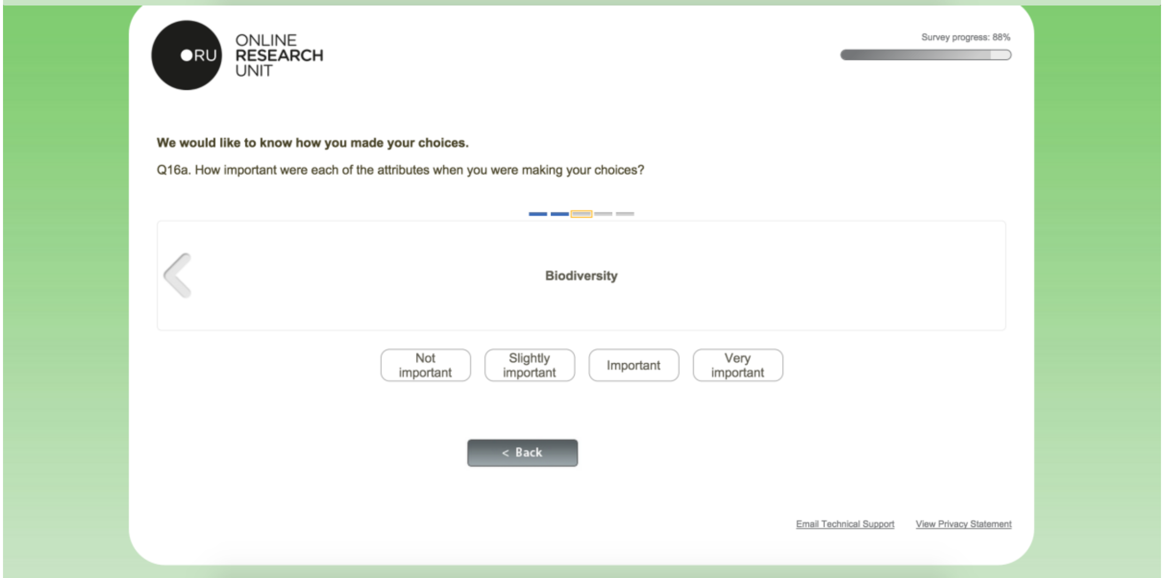
ONLINE RESEARCH UNIT
Survey progress: 88%
We would like to know how you made your choices.
Q16a. How important were each of the attributes when you were making your choices?
Biodiversity
Not important
Slightly important
Important
Very important
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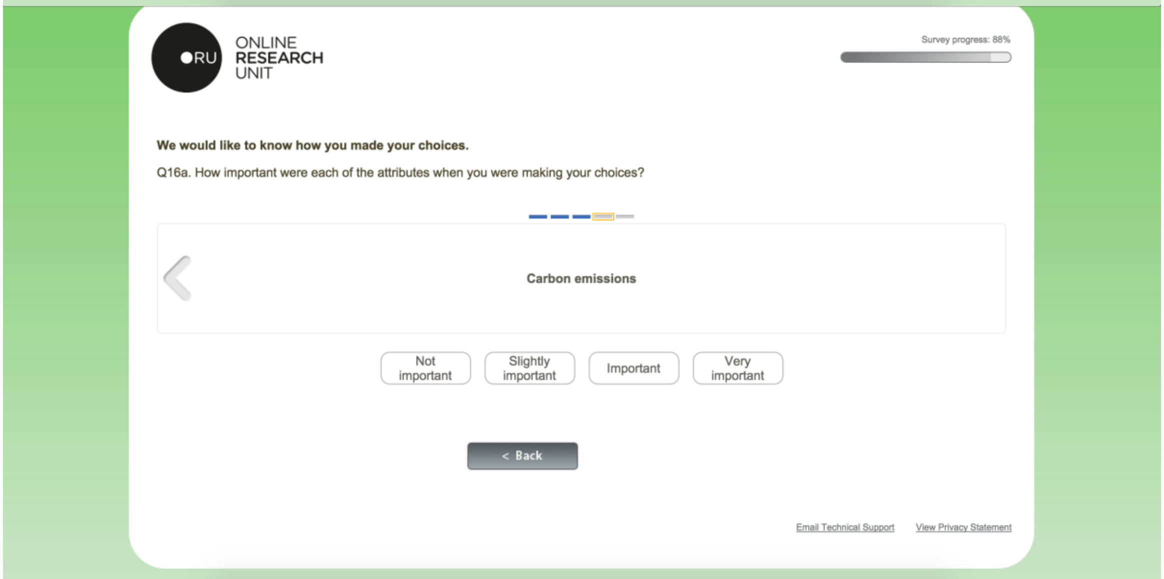
ONLINE RESEARCH UNIT
Survey progress: 88%
We would like to know how you made your choices.
Q16a. How important were each of the attributes when you were making your choices?
Carbon emissions
Not important
Slightly important
Important
Very important
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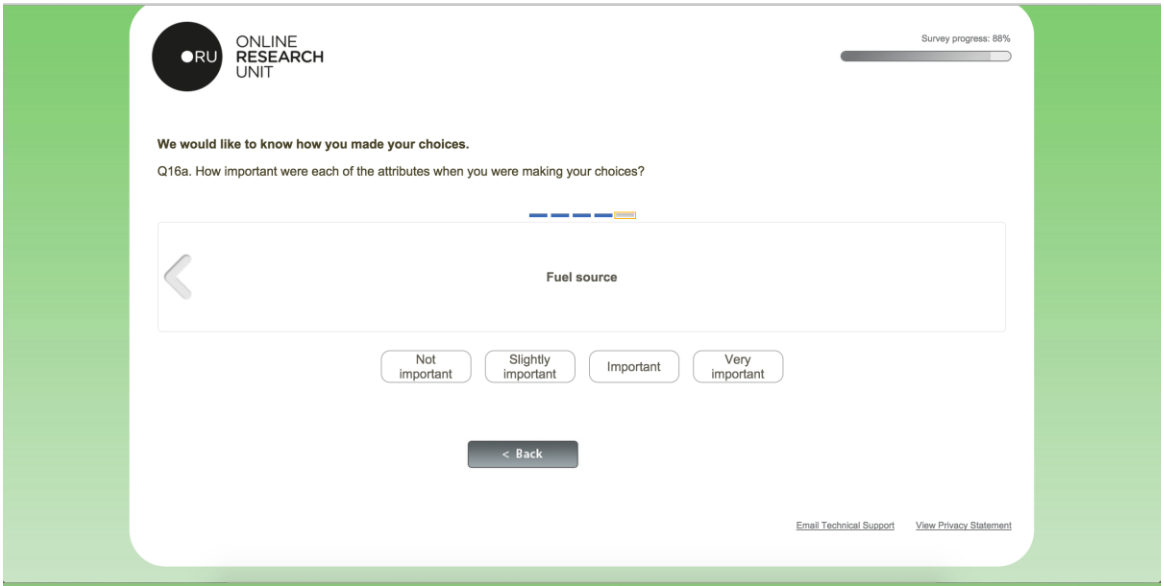
ONLINE RESEARCH UNIT
Survey progress: 88%
We would like to know how you made your choices.
Q16a. How important were each of the attributes when you were making your choices?
Fuel source
Not important
Slightly important
Important
Very important
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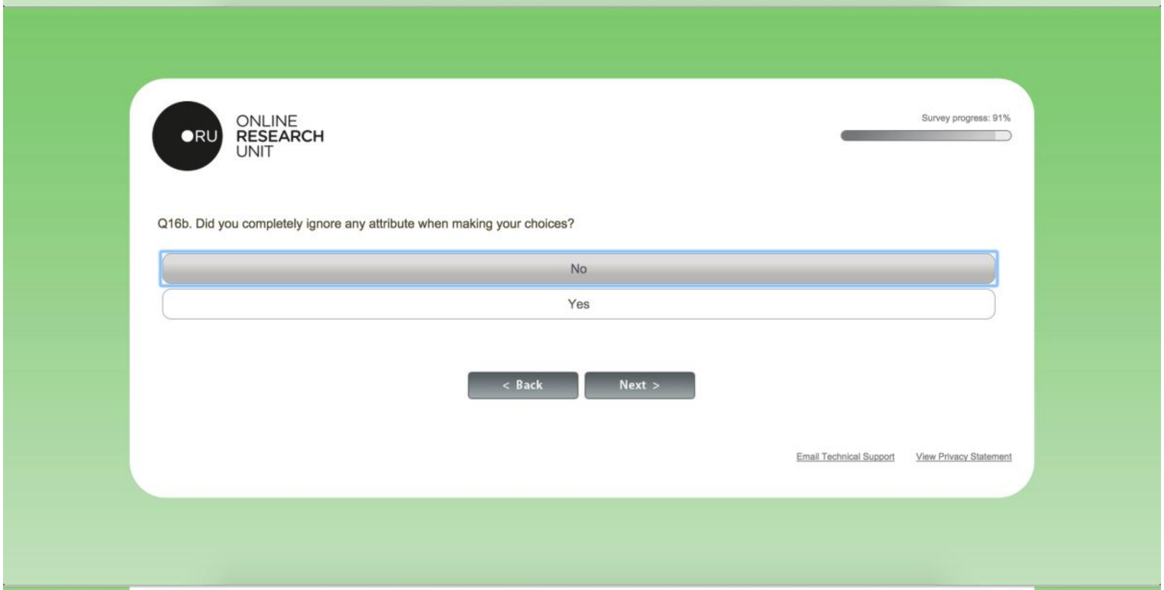
ONLINE RESEARCH UNIT
Survey progress: 91%
Q16b. Did you completely ignore any attribute when making your choices?
No
Yes
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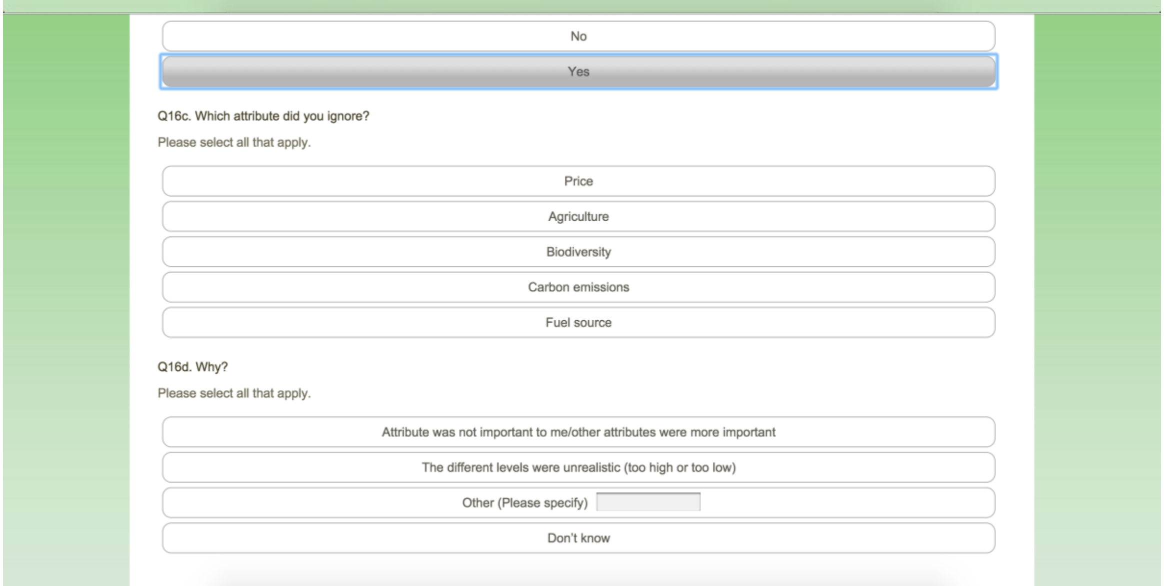
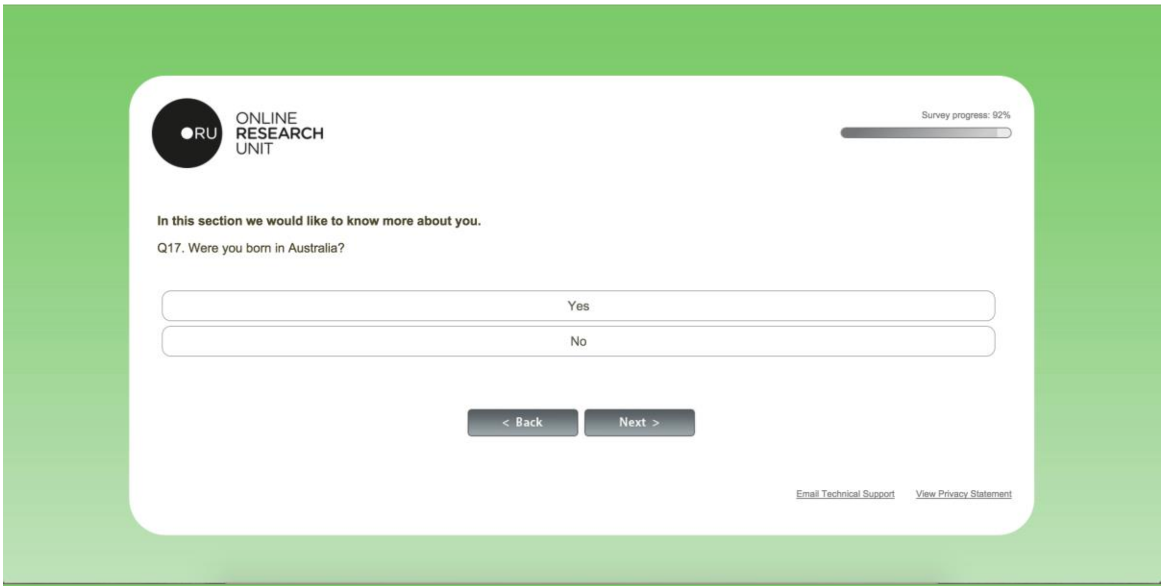

No
Yes
Q16c. Which attribute did you ignore?
Please select all that apply.
Price
Agriculture
Biodiversity
Carbon emissions
Fuel source
Q16d. Why?
Please select all that apply.
Attribute was not important to me/other attributes were more important
The different levels were unrealistic (too high or too low)
Other (Please specify)
Don't know


ONLINE RESEARCH UNIT

Survey progress: 92%

In this section we would like to know more about you.

Q17. Were you born in Australia?

Yes

No

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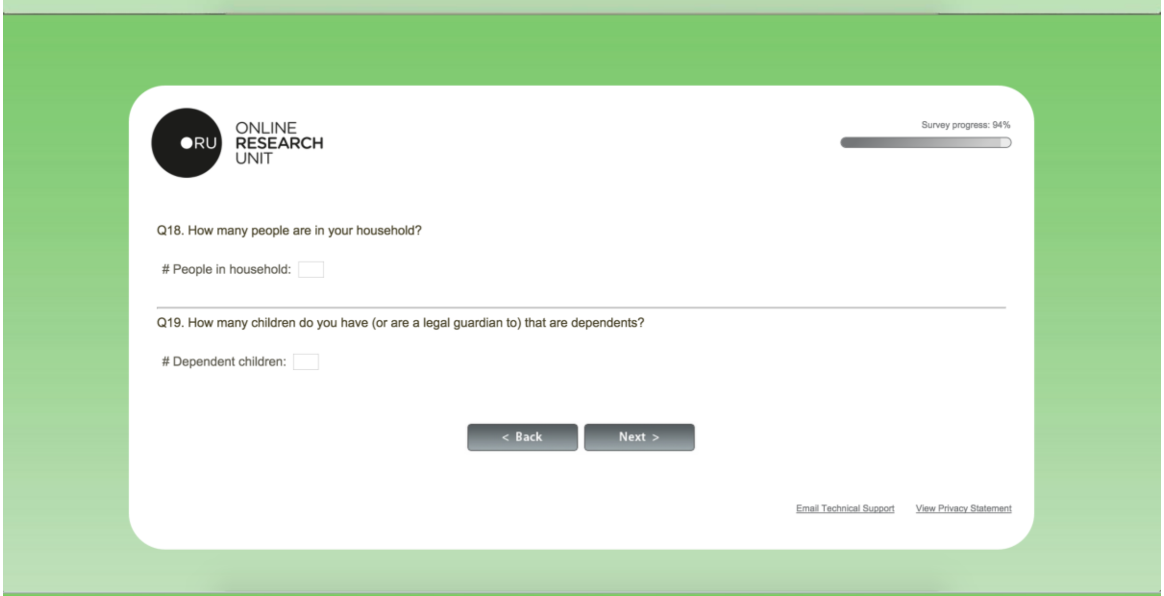
ONLINE RESEARCH UNIT

Survey progress: 94%

Q18. How many people are in your household?

People in household:

Q19. How many children do you have (or are a legal guardian to) that are dependents?

Dependent children:

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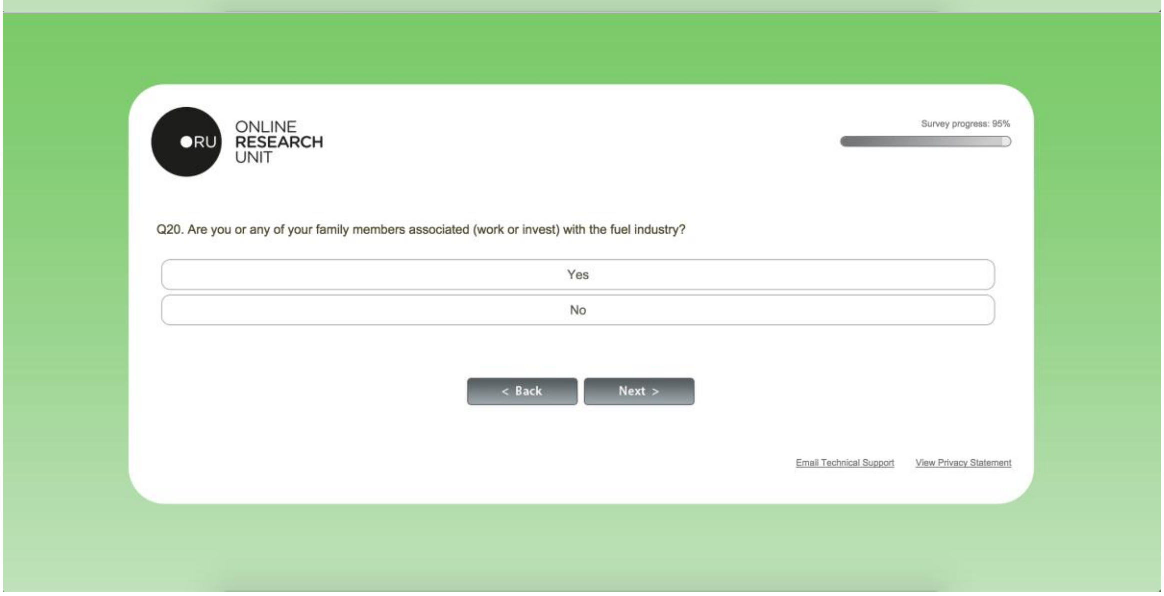
ONLINE RESEARCH UNIT

Survey progress: 95%

Q20. Are you or any of your family members associated (work or invest) with the fuel industry?

Yes

No

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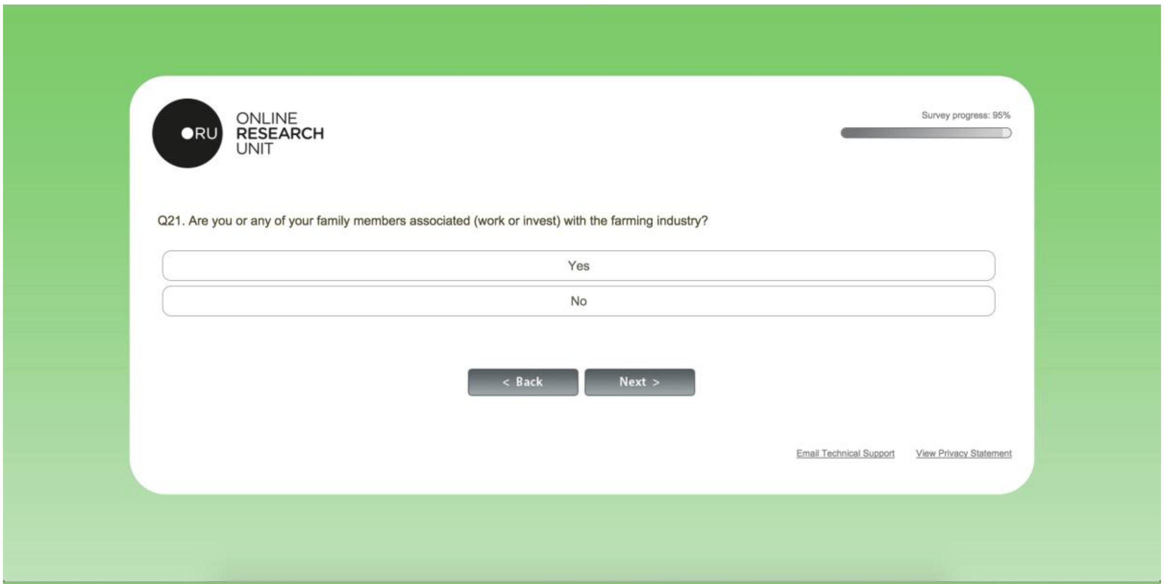

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Survey progress: 95%

Q21. Are you or any of your family members associated (work or invest) with the farming industry?

Yes

No

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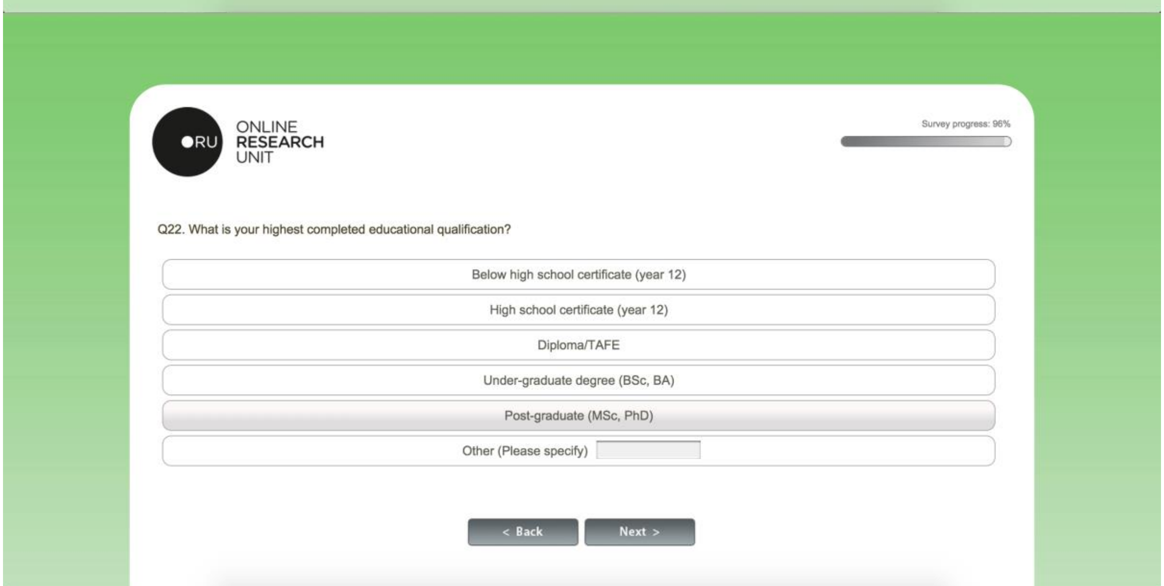

ONLINE RESEARCH UNIT

Survey progress: 96%

Q22. What is your highest completed educational qualification?

Below high school certificate (year 12)

High school certificate (year 12)

Diploma/TAFE

Under-graduate degree (BSc, BA)

Post-graduate (MSc, PhD)

Other (Please specify)

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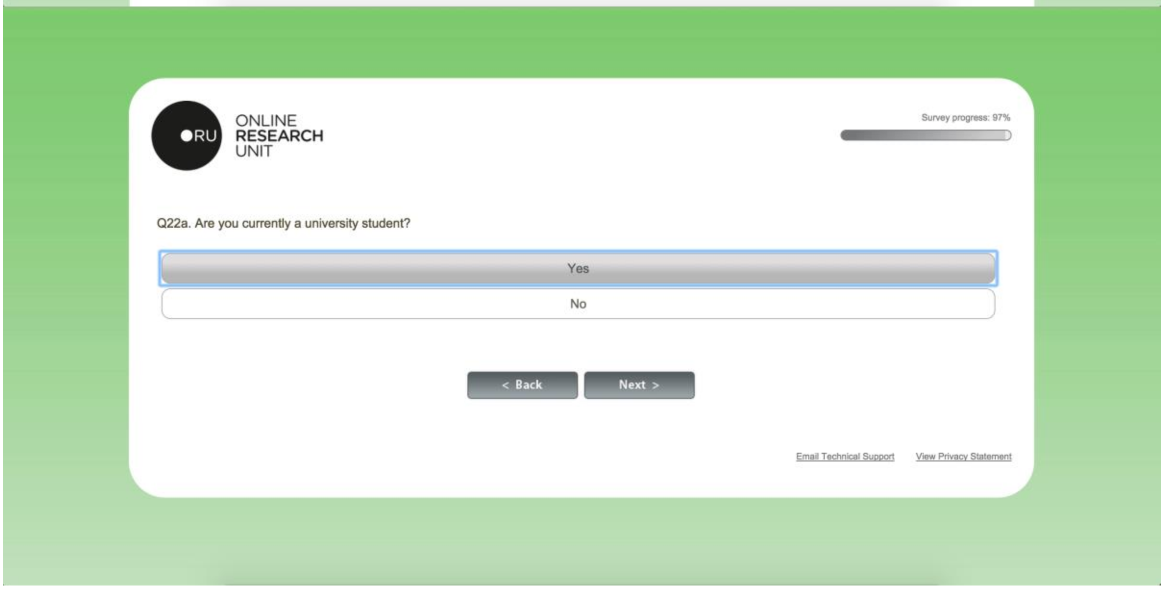

ONLINE RESEARCH UNIT

Survey progress: 97%

Q22a. Are you currently a university student?

Yes

No

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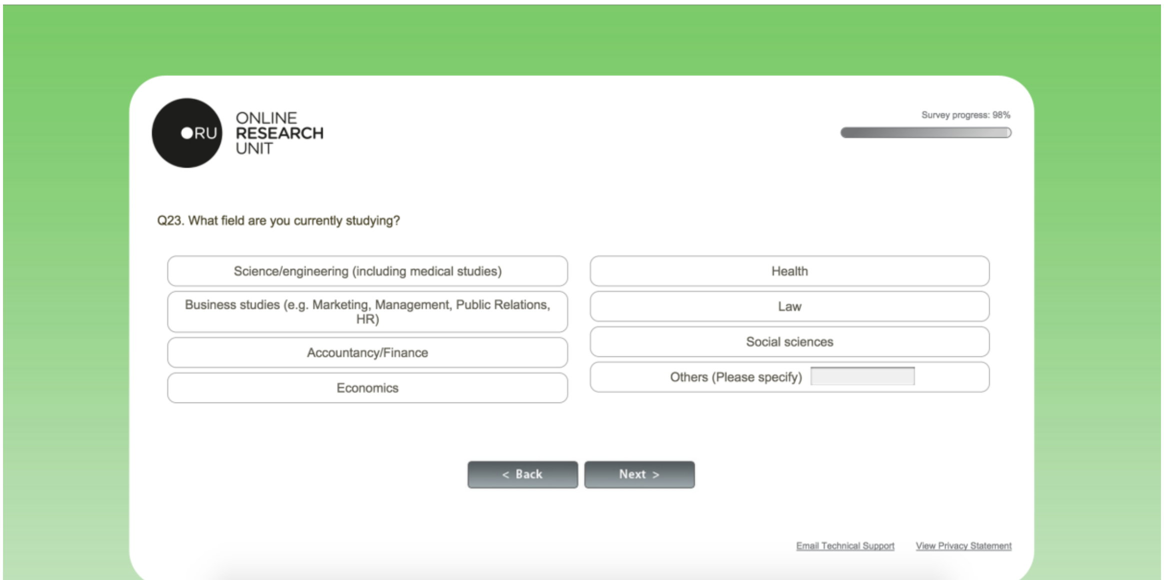
ONLINE RESEARCH UNIT
Survey progress: 98%
Q23. What field are you currently studying?
Science/engineering (including medical studies)
Business studies (e.g. Marketing, Management, Public Relations, HR)
Accountancy/Finance
Economics
Health
Law
Social sciences
Others (Please specify)
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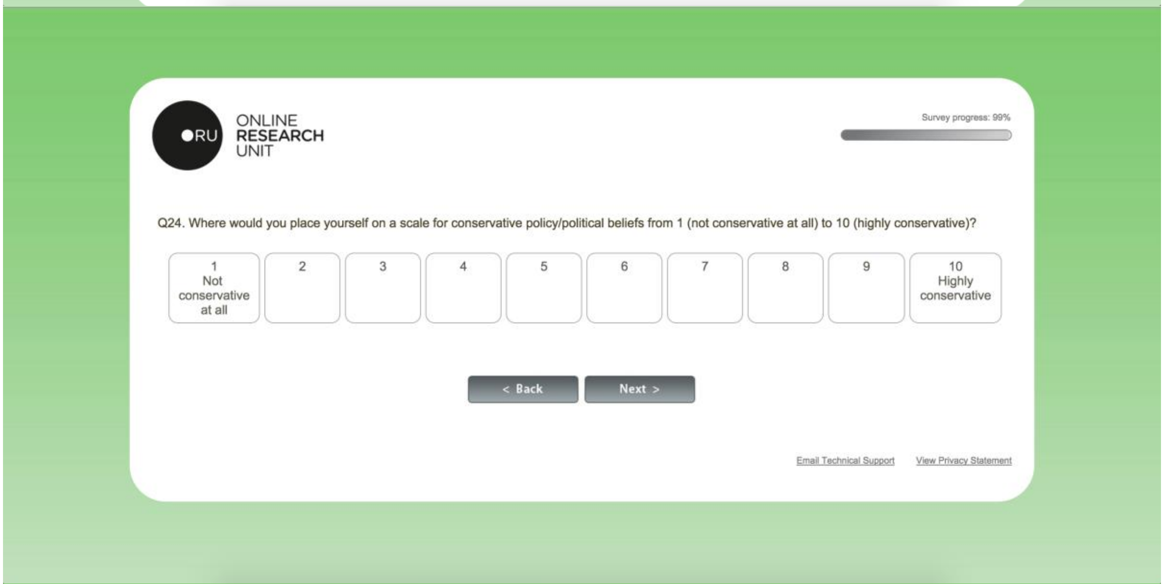
ONLINE RESEARCH UNIT
Survey progress: 99%
Q24. Where would you place yourself on a scale for conservative policy/political beliefs from 1 (not conservative at all) to 10 (highly conservative)?
1 Not conservative at all
2
3
4
5
6
7
8
9
10 Highly conservative
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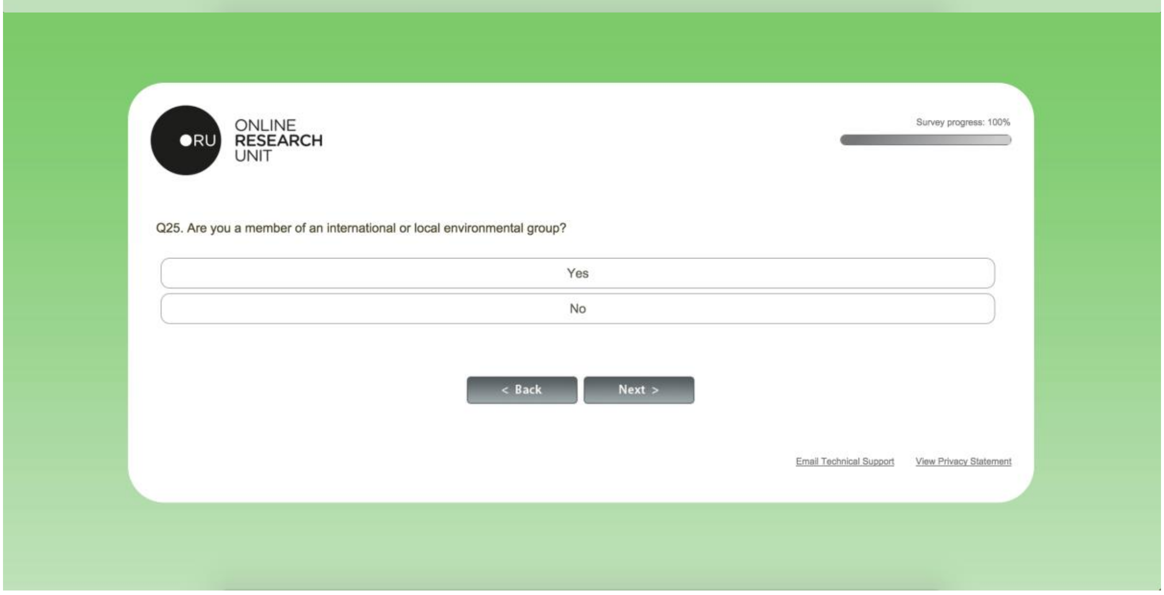
ONLINE RESEARCH UNIT
Survey progress: 100%
Q25. Are you a member of an international or local environmental group?
Yes
No
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Q26. What was the approximate pre-tax **personal** income you earned last year for the entire year?

As for all your answers, the information you provide here is strictly confidential.

Nil income

$1 - $20,799

$20,800 - $41,599

$41,600 - $64,999

$65,000-$77,999

$78,000-$103,999

$104,000-$129,999

$130,000-$155,999

$156,000-$181,999

$182,000-$207,999

$208,000-$259,999

$260,000 or more

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This concludes the survey. You have received 25 points.

Important Note: Your reward points have been awarded automatically. You no longer need to enter your ID to be awarded your rewards.

~

Thank you very much for your valuable time and feedback.

CODE 1 ERROR: Your ID Number has already submitted for this survey. Please email: support@theoru.com with your ID Number and the survey number and we can check the status of your points.

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Appendix F

A MNL model was run initially with the sample using only choice attributes and incorporating socio-demographic and psychographic variables. However, after carrying out the Hausman-McFadden test for the IIA assumption with the choice attribute-only estimation (see Appendix G), it was identified that this estimation would be inappropriate. Hence, RPL estimations were used in subsequent models. Both MNL models are shown in Table F.1 below.

Table F.1: MNL estimations for pooled sample.

	Choice attributes only			**Full MNL model**		
Variable	Coeff.		S.E.	Coeff.		S.E.
Choice attributes						
EMISSIONS	-1.397	***	0.065	-1.398	***	0.065
SOURCE	0.743	***	0.044	0.744	***	0.044
FOOD PRICE	-2.966	***	0.154	-2.977	***	0.154
BIODIVERSITY	0.991	***	0.059	0.995	***	0.059
PRICE	-3.063	***	0.145	-3.065	***	0.145
ASC	0.430	***	0.046	0.771	***	0.195
Socio-demographic variables						
AGE				0.051	**	0.021
GENDER				-0.334	***	0.071
PARENT				0.167	**	0.075
FUEL INDUSTRY				-0.467	*	0.251
OTHER TERTIARY				0.249	***	0.074
INCOME				-0.096	***	0.017
Psychographic variables						
FOSSIL				0.235	**	0.098
MEMBER				-0.667	***	0.177
N	556			556		
Adj. R^2	0.131			0.142		
LL	-4226.6			-4166.4		
AIC	1.903			1.880		

'***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%

Appendix G

The Hausman-McFadden (1984) test for the IIA assumption was used to assess if the MNL estimation was appropriate for the sample. For this test, separate models were run by restricting/removing each alternative. This test was attempted for the attribute-only model and the base model (including significant socio-demographic and psychographic variables). However, models for the latter could not be estimated. The estimations for the restricted models is given in Table G.1. The p-values indicate that the IIA assumption can be rejected given that removing each alternative (A and B) affected the probability of choosing the unrestricted options. The test could not be carried out for the model that restricted option C and produced the error message "Could not carry out Hausman test for IIA. Difference matrix is not positive definite". This is potentially due to the lack of variability when it is dropped as the utility function was the same for options A and B (Hensher et al., 2005a).

Table G.1: Restricted MNL estimations for Hausman-McFadden test.

	Restricting option A			Restricting option B			Restricting option C		
Variable	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.
EMISSIONS	-1.743	***	0.127	-1.186	***	0.123	-1.212	***	0.066
SOURCE	0.620	***	0.088	0.947	***	0.082	0.663	***	0.020
FOOD PRICE	-3.310	***	0.296	-2.979	***	0.289	-2.547	***	0.145
BIODIVERSITY	0.923	***	0.113	1.108	***	0.116	0.856		fixed
PRICE	-4.244	***	0.282	-2.280	***	0.284	-2.561		fixed
ASC	0.380	***	0.070	0.530	***	0.063	0.000		fixed
N	556			556			556		
Num of obs.	2866			2861			3169		
Skipped	1582			1587			1279		
Adj. R^2	0.097			0.082			0.244		
LL	-1775.6			-1802.4			-1658.4		
AIC	1.243			1.264			1.050		
Chi-sq stat.	40.6			26.1			Could not carry out Hausman test		
P(C>c)	0.000			0.000					

'***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%

Appendix H

Protest models were run by dropping respondents who chose the same alternative for every choice set. Although the numbers for protesting were relatively small compared to the total sample size, each of the protest models performed better than the base RPL model for the pooled sample by AIC and adjusted R^2. The separate protest models are shown in Table H.1 below.

Table H.1: Panel-RPL estimations for protesting of each alternative.

	Protesting A			Protesting B			Protesting C		
Variable	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.
Choice attributes									
EMISSIONS	-2.048	***	0.122	-1.933	***	0.112	-1.792	***	0.105
SOURCE	0.947	***	0.086	0.937	***	0.085	0.894	***	0.074
FOOD PRICE	-4.589	***	0.284	-4.381	***	0.269	-4.089	***	0.257
BIODIVERSITY	1.395	***	0.105	1.388	***	0.104	1.246	***	0.097
PRICE	-4.457	***	0.267	-4.229	***	0.262	-3.879	***	0.241
ASC	0.918	***	0.250	0.873	***	0.247	0.460	*	0.251
Socio-demographic variables									
AGE	0.113	***	0.028	0.107	***	0.028	0.058	**	0.028
GENDER	-0.281	***	0.094	-0.260	***	0.092	-0.069		0.094
PARENT	0.194	*	0.100	0.183	*	0.097	0.169	*	0.098
FUEL INDUSTRY	-0.818	***	0.295	-0.875	***	0.296	-1.016	***	0.334
OTHER TERTIARY	0.350	***	0.101	0.228	**	0.098	0.206	**	0.099
INCOME	-0.123	***	0.023	-0.130	***	0.022	-0.090	***	0.022
Psychographic variables									
FOSSIL	0.286	**	0.128	0.346	***	0.125	0.169		0.124
MEMBER	-0.681	***	0.215	-0.690	***	0.212	-0.945	***	0.236
N	547			551			519		
Adj. R^2	0.198			0.193			0.190		
LL	-4807.5			-4842.7			-4561.4		
AIC	1.767			1.779			1.784		

'***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%

Appendix I

In this section, the models presented are those including the assumed protesting respondents. The full-sample estimation with state-based partitioning for the same four states (NSW, QLD, VIC, WA) is shown in Table I.1. The full-sample estimation for the stated non-attendance models is given in Table I.2. Only the SNA to individual attributes are presented as the estimations for combined SNA were found to perform poorly compared to the base panel-RPL estimation. The full-sample estimation for the inferred non-attendance models, including respective probit estimation for class membership, is shown in Table I.3.

Table I.1: Panel-RPL and WTP estimation partitioned by state† for full sample.

	NSW				QLD				VIC				WA			
Variable	Coeff.		S.E.	WTP	Coeff.		S.E.	WTP	Coeff.		S.E.	WTP	Coeff.		S.E.	WTP
Choice attributes																
EMISSIONS	-1.674	***	0.164	-0.438	-1.857	***	0.283	-0.361	-2.019	***	0.233	-0.459	-1.797	***	0.425	-0.918
SOURCE	0.735	***	0.131	0.192	0.928	***	0.212	0.181	1.125	***	0.171	0.256	0.799	***	0.285	0.408
FOOD PRICE	-3.431	***	0.378	-0.898	-5.446	***	0.770	-1.059	-4.891	***	0.587	-1.111	-3.168	***	0.788	-1.619
BIODIVERSITY	1.229	***	0.167	0.322	1.349	***	0.248	0.262	1.356	***	0.208	0.308	1.121	***	0.325	0.573
PRICE	-3.823	***	0.394		-5.142	***	0.657		-4.402	***	0.486		-1.957	**	0.834	
ASC	0.533		0.392		2.470	***	0.714		0.239		0.454		2.235	**	1.116	
Socio-demographic variables																
AGE	0.138	***	0.045		-0.056		0.072		0.205	***	0.054		-0.103		0.124	
GENDER	-0.205		0.157		-0.913	***	0.230		-0.239		0.178		-0.350		0.366	
PARENT	0.196		0.164		0.036		0.222		0.097		0.199		0.905	**	0.354	
FUEL INDUSTRY	-0.445		0.468		-3.156	***	0.897		-0.359		0.511		-0.551		1.241	
OTHER TERTIARY	-0.029		0.171		1.033	***	0.234		0.431	**	0.207		0.355		0.390	
INCOME	-0.129	***	0.034		-0.049		0.059		-0.045		0.044		-0.201	**	0.097	
Psychographic variables																
FOSSIL	0.198		0.166		0.146		0.374		0.485		0.303		-0.259		0.631	
MEMBER	-0.003		0.308		-0.318		0.671		-1.676	***	0.411		-1.674		1.183	
N	183				108				149				47			
Adj. R^2	0.168				0.216				0.191				0.194			
LL	-1608.4				-949.2				-1309.5				-413.1			
AIC	1.841				1.747				1.796				1.827			

†Excludes ACT, NT, NA, and TAS. '***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%

Table I.2: Panel-RPL for SNA to choice attributes for full sample.

	SNA – EMISSIONS (n=28)			SNA – SOURCE (n=53)			SNA - FOOD PRICE (n=29)			SNA – BIODIVERSITY (n=34)			SNA – PRICE (n=27)		
Variable	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.
Choice attributes															
EMISSIONS	-1.967	***	0.112	-1.866	***	0.108	-1.891	***	0.110	-1.916	***	0.111	-1.908	***	0.110
SOURCE	0.889	***	0.084	0.818	***	0.085	0.891	***	0.084	0.897	***	0.084	0.904	***	0.084
FOOD PRICE	-4.269	***	0.263	-4.175	***	0.259	-4.387	***	0.273	-4.337	***	0.267	-4.294	***	0.267
BIODIVERSITY	1.350	***	0.101	1.287	***	0.099	1.342	***	0.103	1.411	***	0.106	1.360	***	0.102
PRICE	-4.202	***	0.254	-4.123	***	0.248	-4.260	***	0.263	-4.254	***	0.260	-4.418	***	0.267
ASC	0.788	***	0.246	0.666	***	0.237	0.802	***	0.247	0.812	***	0.247	0.812	***	0.247
Socio-demographic variables															
AGE	0.104	***	0.028	0.101	***	0.027	0.107	***	0.028	0.106	***	0.028	0.107	***	0.028
GENDER	-0.232	**	0.092	-0.232	***	0.089	-0.239	***	0.092	-0.236	**	0.093	-0.243	***	0.092
PARENT	0.177	*	0.097	0.169	*	0.094	0.174	*	0.097	0.175	*	0.097	0.177	*	0.097
FUEL INDUSTRY	-0.870	***	0.289	-0.805	***	0.287	-0.891	***	0.290	-0.886	***	0.289	-0.866	***	0.289
OTHER TERTIARY	0.290	***	0.098	0.271	***	0.095	0.298	***	0.098	0.298	***	0.098	0.294	***	0.098
INCOME	-0.118	***	0.022	-0.114	***	0.021	-0.119	***	0.022	-0.119	***	0.022	-0.118	***	0.022
Psychographic variables															
FOSSIL	0.274	**	0.125	0.307	**	0.120	0.273	**	0.125	0.269	**	0.126	0.270	**	0.126
MEMBER	-0.656	***	0.212	-0.666	***	0.208	-0.666	***	0.212	-0.659	***	0.213	-0.677	***	0.212
N	556			556			556			556			556		
Adj. R^2	0.190			0.182			0.189			0.190			0.192		
LL	-4886.6			-4886.6			-4886.6			-4886.6			-4886.6		
AIC	1.784			1.803			1.788			1.784			1.781		

'***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%

Table I.3: Panel-LCM for INA to choice attributes for full sample.

	Class 1: Emissions NA			Class 2: Source NA			Class 3: Food price NA			Class 4: Biodiversity NA			Class 5: Fuel price NA			Class 6: Full NA		
Variable	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.
EMISSIONS	0.000		fixed	-2.033	***	0.116	-2.033	***	0.116	-2.033	***	0.116	-2.033	***	0.116	0.000		fixed
SOURCE	2.021	***	0.127	0.000		fixed	2.021	***	0.127	2.021	***	0.127	2.021	***	0.127	0.000		fixed
FOOD PRICE	-4.818	***	0.298	-4.818	***	0.298	0.000		fixed	-4.818	***	0.298	-4.818	***	0.298	0.000		fixed
BIODIVERSITY	1.663	***	0.121	1.663	***	0.121	1.663	***	0.121	0.000		fixed	1.663	***	0.121	0.000		fixed
PRICE	-4.917	***	0.298	-4.917	***	0.298	-4.917	***	0.298	-4.917	***	0.298	0.000		fixed	0.000		fixed
Class probability	0.050	***	0.019	0.446	***	0.034	0.074	***	0.023	0.104	***	0.026	0.079	***	0.024	0.248	***	0.029
N	556																	
Adj. R^2	0.162																	
LL	-4886.6																	
AIC	1.843																	
Class membership probit models																		
Variable	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.
Socio-demographic variables																		
AGE	-0.111	**	0.045	-0.005		0.028	-0.111	***	0.041	-0.084	**	0.036	-0.108	***	0.040	-0.035		0.031
GENDER	-0.392	***	0.139	0.026		0.085	-0.304	**	0.123	-0.221	**	0.112	-0.192		0.119	-0.409	***	0.096
PARENT	-0.118		0.198	0.023		0.117	-0.212		0.177	0.001		0.155	-0.172		0.171	0.084		0.128
FUEL INDUSTRY	-0.541		0.711	-0.508		0.342	-0.124		0.426	-0.412		0.474	-0.329		0.481	0.752	**	0.319
OTHER TERTIARY	-0.148		0.206	0.043		0.120	-0.339	*	0.196	-0.108		0.161	-0.118		0.175	0.113		0.130
INCOME	-0.034		0.040	0.002		0.024	-0.001		0.033	-0.056	*	0.033	-0.068	*	0.036	-0.043		0.027
Psychographic variables																		
FOSSIL	-0.374	*	0.201	-0.170		0.136	-0.404	**	0.183	-0.326	*	0.169	-0.311	*	0.182	0.174		0.154
MEMBER	-0.026		0.423	-0.338		0.238	0.394		0.289	0.298		0.288	0.411		0.292	-0.060		0.261
LL	-116.7			-382.1			-151.9			-192.4			-161.3			-311.3		
AIC	0.449			1.389			0.575			0.721			0.609			1.116		
Hosmer-Lemeshow	13.023			7.716			10.617			15.535			16.061			7.716		
P-value	0.111			0.462			0.224			0.050			0.042			0.519		

'***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%

Appendix J

LCM estimations for the sample excluding protest responses and using only choice attributes is given in Table J.1 and Table J.2. The best LCM estimation was selected based on AIC. Upon estimating with a number of classes, it was found that a nine-class estimation produced the best LCM in terms of AIC and adjusted-R^2. This model also performs better than the base panel-RPL model that included other explanatory variables. However, with the large number of classes, some estimates appeared unrealistic and the model was difficult to interpret even with the separate probit estimations of class probabilities.

Table J.1: Panel-LCM estimation for choice attributes (Class 1-5).

	Class 1			Class 2			Class 3			Class 4			Class 5		
Variable	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.
EMISSIONS	-1.102	*	2.107	-0.674		0.531	-1.023	***	0.208	0.682		0.935	2.257		84.89
SOURCE	5.496		3.148	0.438		0.366	0.216	*	0.119	-0.097		0.760	2.375		102.4
FOOD PRICE	-9.562		8.094	-9.361	***	1.860	-0.416		0.473	-1.323		1.844	1.051		143.6
BIODIVERSITY	-1.905		1.665	3.593	***	0.887	0.739	***	0.182	1.268		0.879	-33.42		9930
PRICE	1.654		5.158	-6.586	***	1.336	-0.945	*	0.487	1.454		2.030	-0.481		333.3
ASC	-6.857		2665	-1.947	***	0.719	-0.283		0.221	1.479	**	0.700	17.47		5064
Class probability	0.057	***		0.077	***		0.181	***		0.032	**		0.007		
N	505														
Adj. R^2	0.294														
LL	-4438.4														
AIC	1.570														
Class membership probit models															
Variable	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.
Socio-demographic variables															
AGE	-0.064		0.043	-0.100	**	0.042	-0.063	*	0.034	-0.115	**	0.056	-0.036		0.092
GENDER	-0.386	***	0.137	-0.305	**	0.126	-0.339	***	0.103	-0.455	***	0.171	-0.888	***	0.317
PARENT	-0.018		0.195	-0.259		0.190	0.027		0.144	0.034		0.243	0.364		0.391
FUEL INDUSTRY	-2.939		18.263	0.143		0.494	0.358		0.345	-1.071		2.364	-6.372		$2.17E^7$
OTHER TERTIARY	0.003		0.193	-0.270		0.200	-0.076		0.151	-0.133		0.258	0.086		0.382
INCOME	-0.111	**	0.044	-0.017		0.037	0.012		0.029	-0.094	*	0.054	-0.272	**	0.122
Psychographic variables															
FOSSIL	-0.242		0.210	-0.320	*	0.190	-0.209		0.160	-0.337		0.242	-0.274		0.414
MEMBER	0.120		0.403	-0.997		0.692	-0.086		0.282	-1.165		1.779	-6.977		$2.16E^7$
LL	-120.9			-138.3			-239.0			-71.5			-25.4		
AIC	0.51			0.579			0.965			0.313			0.132		
Hosmer-Lemeshow	29.385			10.332			2.728			6.661			33.083		
P-value	0.000			0.243			0.950			0.574			0.000		

'***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%. E^n is exponential to the n^{th} power.

Table J.2: Panel-LCM estimation for choice attributes (Class 6-9).

	Class 6			Class 7			Class 8			Class 9		
Variable	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.
EMISSIONS	-1.021	***	0.153	-23.41	***	8.291	0.616		0.905	-4.660	***	0.288
SOURCE	0.589	***	0.138	13.83	**	5.375	2.076	***	0.709	1.642	***	0.169
FOOD PRICE	-1.626	***	0.421	-36.16	***	13.98	-17.38	***	5.126	-11.21	***	0.709
BIODIVERSITY	0.109		0.201	20.15	***	7.414	-3.551	**	1.640	3.567	***	0.255
PRICE	-0.803	**	0.344	-64.58	***	24.70	-17.59	***	4.411	-11.03	***	0.658
ASC	-2.896	***	0.825	-7.614	***	2.462	1.973	**	0.896	2.913	***	0.171
Class probability	0.182	***		0.072	***		0.042	***		0.350	***	
N	505											
Adj. R^2	0.294											
LL	-4438.4											
AIC	1.570											
Class membership probit models												
Variable	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.	Coeff.		S.E.
Socio-demographic variables												
AGE	-0.084	**	0.034	-0.145	***	0.044	-0.109	**	0.049	-0.008		0.030
GENDER	-0.150		0.102	-0.212	*	0.128	-0.617	***	0.162	-0.125		0.091
PARENT	0.066		0.143	-0.418	**	0.197	0.142		0.213	0.047		0.128
FUEL INDUSTRY	0.393		0.345	-0.194		0.472	0.090		0.579	-1.056	**	0.518
OTHER TERTIARY	-0.157		0.153	-0.299		0.212	-0.106		0.227	0.252	*	0.128
INCOME	-0.022		0.029	0.012		0.035	-0.054		0.044	-0.063	**	0.026
Psychographic variables												
FOSSIL	-0.303	*	0.159	-0.435	**	0.192	-0.151		0.241	0.046		0.147
MEMBER	0.674	***	0.244	0.439		0.301	-0.247		0.544	-0.225		0.266
LL	-239.6			-131.8			-93.0			-326.8		
AIC	0.964			0.553			0.400			1.290		
Hosmer-Lemeshow	4.995			9.715			14.923			5.842		
P-value	0.758			0.286			0.061			0.665		

'***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%.

Appendix K

The estimation of a panel-RPL model excluding protest responses and with only choice attributes is shown in Table K.1. This estimation was used as a comparison with LCM modelling of INA in terms of model fit and coefficient estimates.

Table K.1: Panel-RPL estimation excluding protestors with choice attributes only.

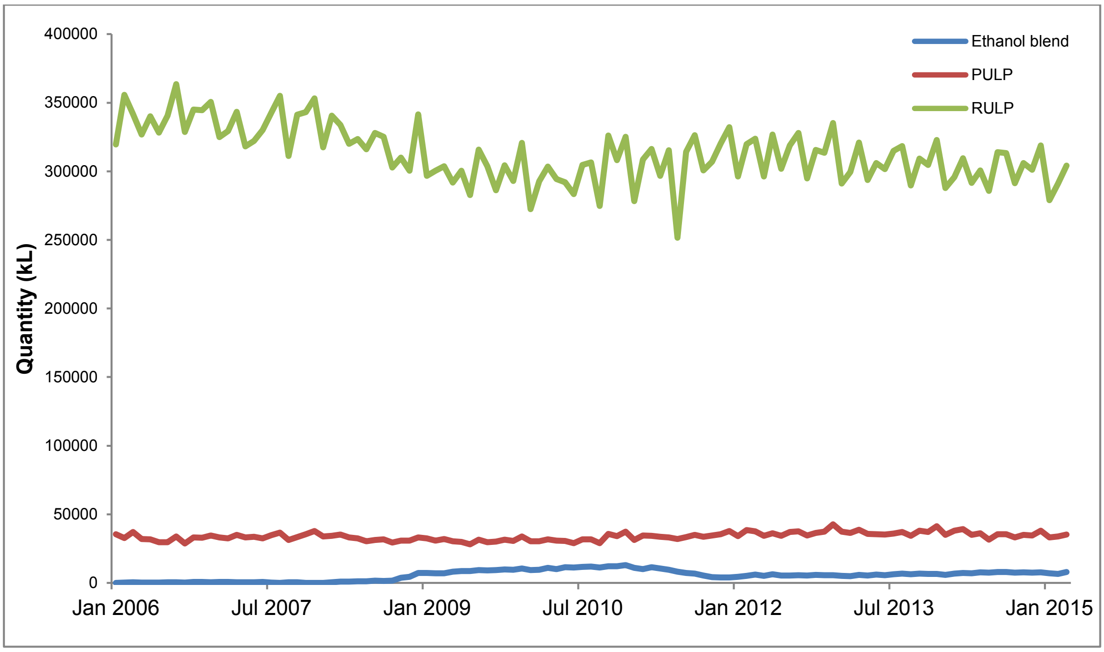
Variable	Coeff.		S.E.	WTP
EMISSIONS	-1.896	***	0.110	-0.470
SOURCE	0.952	***	0.076	0.236
FOOD PRICE	-4.150	***	0.253	-1.028
BIODIVERSITY	1.358	***	0.102	0.336
PRICE	-4.037	***	0.248	-0.470
ASC	0.551	***	0.063	
N	505			
Adj. R^2	0.192			
LL	-4438.4			
AIC	1.778			

'***' Significant at 1%, '**' Significant at 5%, '*' Significant at 10%

Appendix L

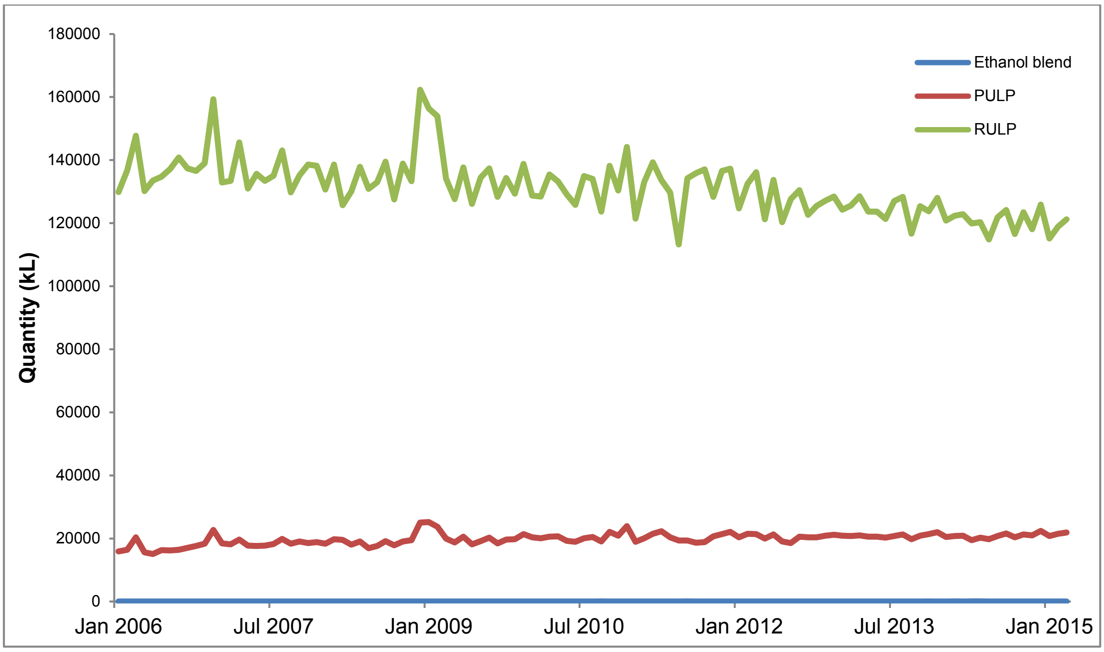
This section covers the trends of consumption of petrol variants; regular unleaded petrol (RULP), premium unleaded petrol (PULP), and ethanol-blends (up to E10) in Victoria (Figure L.1), Western Australia (Figure L.2), South Australia (Figure L.3), Tasmania (Figure L.4), and the Northern Territory (Figure L.5).

Figure L.1: Monthly fuel sales in Victoria (January 2006 - August 2015).



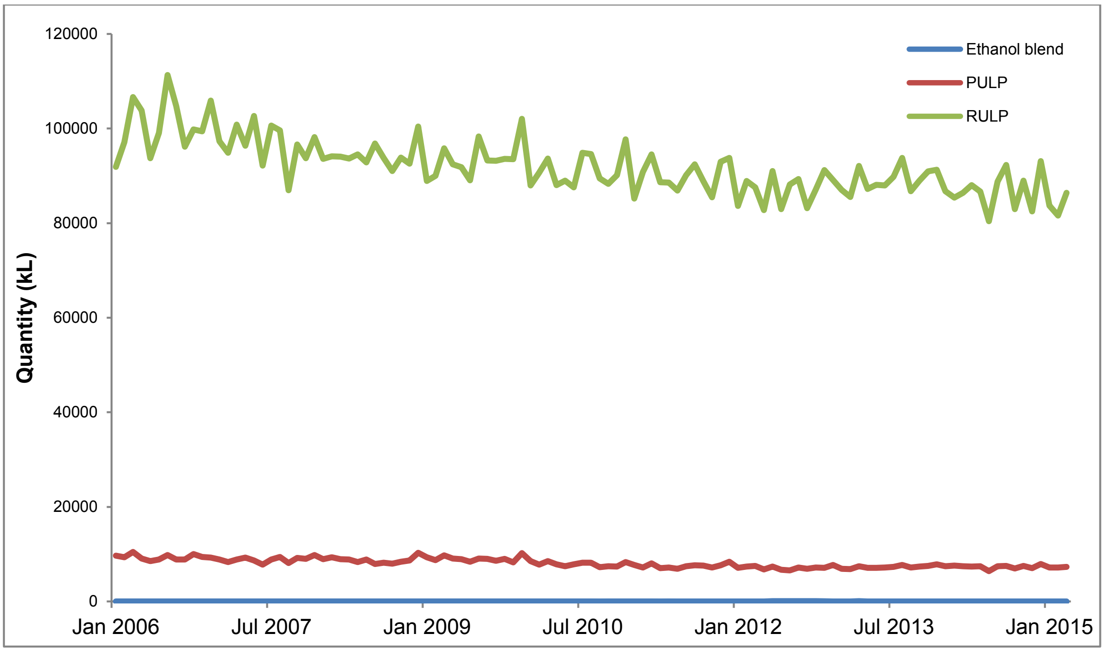
Source: Department of Industry Innovation and Science (n.d.Table 3B).

Figure L.2: Monthly fuel sales in Western Australia January 2006 - August 2015).



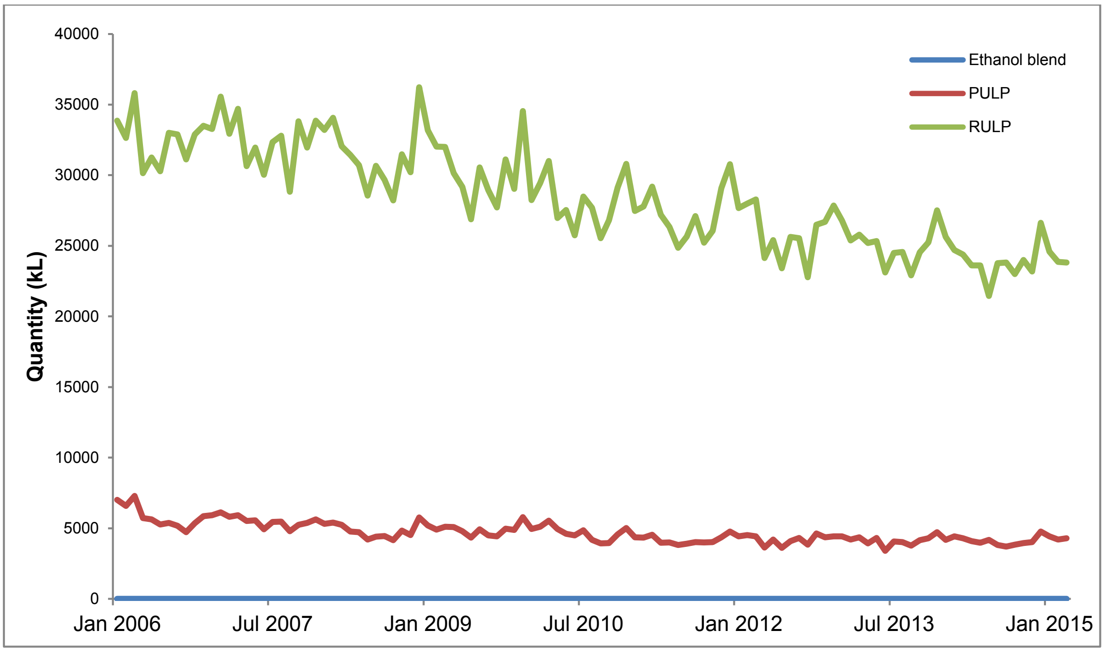
Source: Department of Industry Innovation and Science (n.d.Table 3B).

Figure L.3: Monthly fuel sales in South Australia (January 2006 - August 2015).



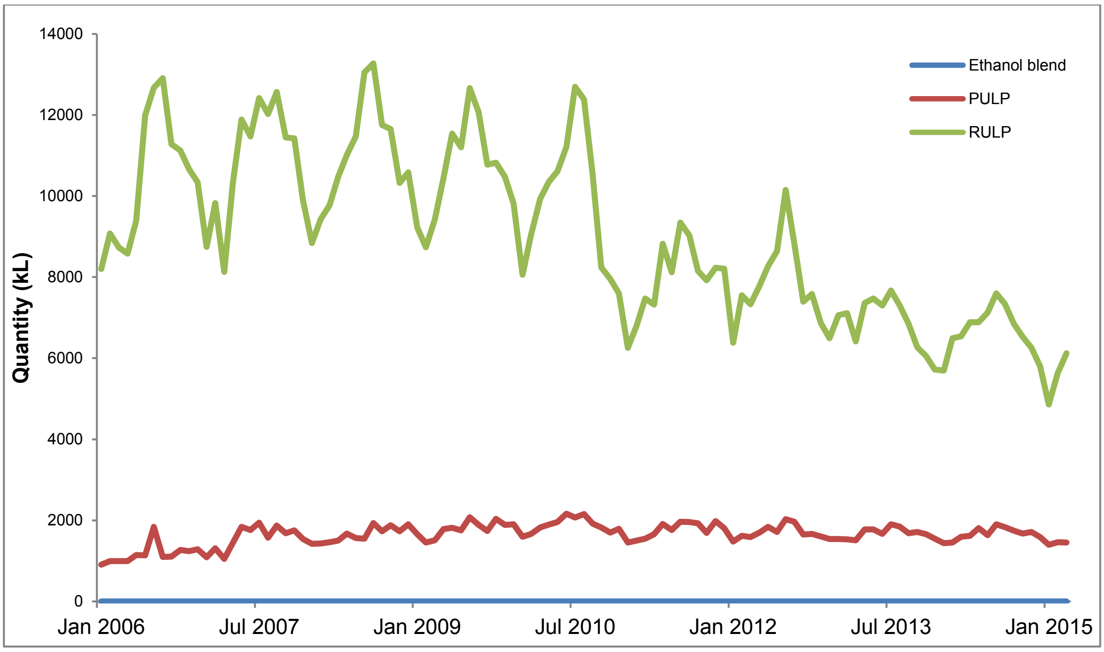
Source: Department of Industry Innovation and Science (n.d.Table 3B).

Figure L.4: Monthly fuel sales in Tasmania (January 2006 - August 2015).



Source: Department of Industry Innovation and Science (n.d.Table 3B).

Figure L.5: Monthly fuel sales in Northern Territory (January 2006 - August 2015).



Source: Department of Industry Innovation and Science (n.d.Table 3B).